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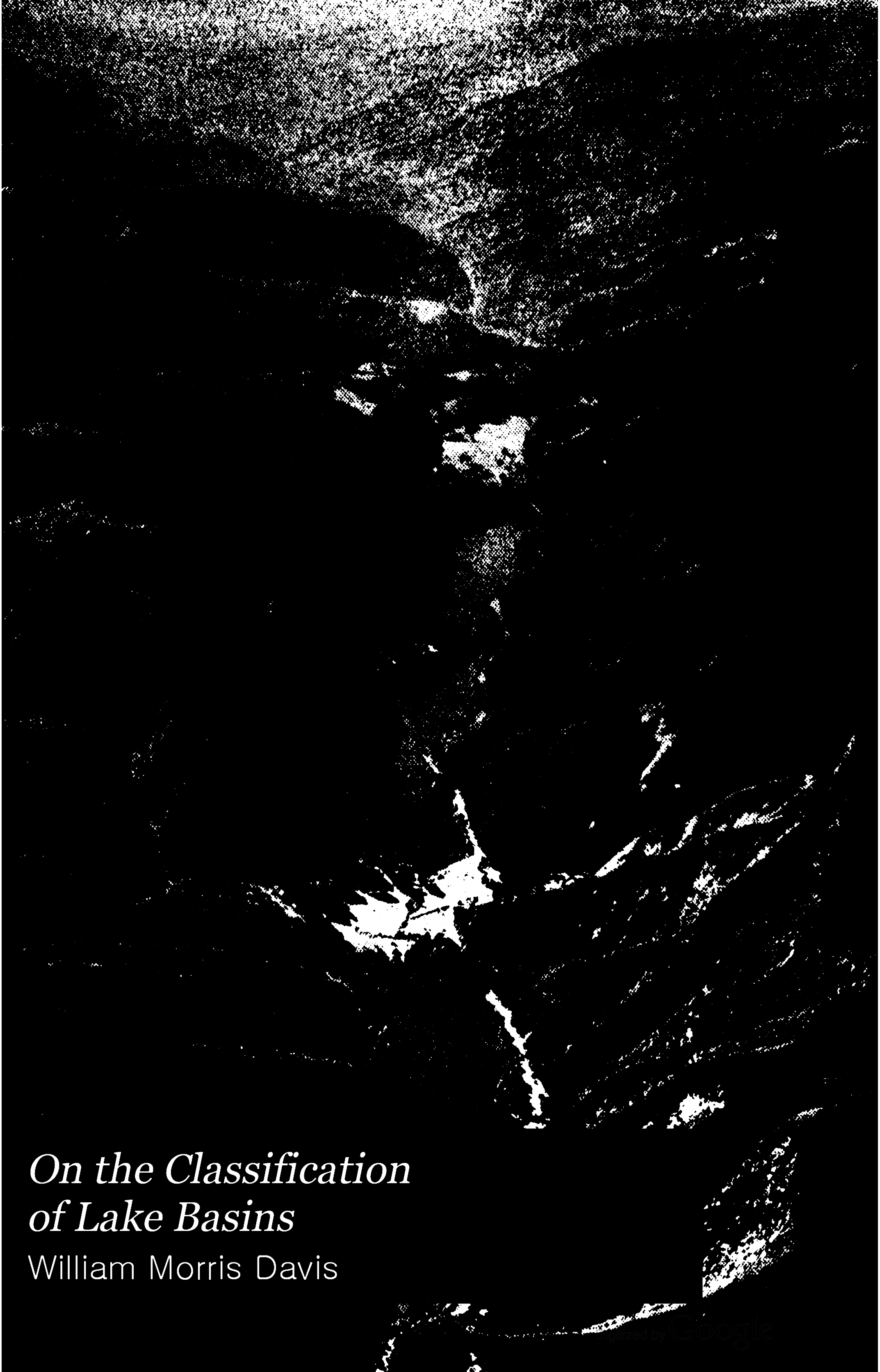

On the Classification of Lake Basins

William Morris Davis

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ON THE
CLASSIFICATION OF LAKE BASINS.

By WILLIAM Morris DAVIS.

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From

W. M. Davis

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ON THE CLASSIFICATION OF LAKE BASINS.

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[From the Proceedings of the Boston Society of Natural History,
Vol. XXI, Jan. 18, 1882.]

ON THE CLASSIFICATION OF LAKE BASINS.

BY WILLIAM MORRIS DAVIS.

Introductory.
Earlier Classifications.

A. Construction or Orographic Basins.
  1. Great Basins.
  2. Mountain Trough Basins.
  3. Fault “
  4. Warped Valley “
  5. Earthquake “
  6. Volcanic Subsidence “
  7. Solution Subsidence “

B. Destruction or Erosion Basins.
  1. Glacial Erosion Basins.
  2. Wind Erosion “
  3. Solution “
  4. Pit-Crater “

C. Obstruction, Barrier or Enclosure Basins.
  1. Fan Delta Barrier Basins.
  2. Ice Barrier “
  3. Moraine Barrier “
  4. Drift Barrier “
  5. Lava Barrier “
  6. Sand Bar “
  7. Barrier Reef “
  8. River Lagoons.
  9. Land Slip Barrier Basins.
  10. Beaver Dams. .
  11. Delta Enclosure Basins.
  12. New Land Basins.
  13. Glacial Drift “
  14. Crater Basins.
  15. Coral Island Lagoons.

INTRODUCTORY. This paper has been prepared largely with a view to use by the author in teaching, where it may serve as a supplement to the presentation of the subject in text-books, and also as a compilation of the more important special papers to which a school-class cannot have ready access. At the same time it may serve as a protest against the too statistical treatment of the topic usually followed, for in the text-books in general use there is a marked neglect of what we may call the true Physical Geography of the Land: there is too much of *what*, *where* and *how many* and not enough of *how* and *why*, so that the study degenerates into Descriptive or Statistical Geography and the properly Physical is lost. The ocean and the atmosphere are better treated; currents and tides, winds, rain and storms have their causes given in addition to the usual description of place and quantity, while mountains and plains, rivers and lakes are generally passed by with but few words of explanation; description is all that is allowed to them. It is not enough to say that the missing part will be found in Geology: something of it is given there, but with a great deal more that is irrelevant to the subject as here considered, and without much that is essential. Perhaps one of the difficulties of the case is that on account of the interlacing of the threads of these studies, no satisfactory order can be found for taking them up independently of each other. A knowledge of Geology comes from the application of existing operations to explain the changes of the past, while a comprehension of Physical Geography constantly requires some reference to the forms of the earth's surface antecedent to those now existing, and at least a suggestion of the methods by which changes are accomplished with the passage of time. In studying mountains, it is not sufficient to say they run in a certain direction and have peaks and passes of such and such heights: it must be taught also that they are the result of long, slow growth at different periods and of varying durations; but the methods of knowing this, and the discussion of the forces engaged in mountain-making come later in Geology. The study of lakes gives excellent opportunity for work of this kind, but as the subject is one of some complexity, it will occasionally carry us beyond ordinary limits, especially under the headings of glacial lakes and drift basins: here, as suggested above, a short exposition of the generally accepted theory of what drift is and how it was deposited is properly introduced; while its fuller study and an examination of the possible causes of the accumulation and motion of the great ice sheets of glacial times, are postponed to their difficult chapter in Geology. The repetition involved in this method of study is a great advantage to the student.

Elementary Geography has already taught something of the distribution of lakes, as for example their prevalence in Minnesota and their absence in Tennessee; then we may ask why are they so unevenly placed — why are there any lakes at all — what is the cause of their basins? With the long answer to this will come a recognition of the distinct forms and surroundings of the different classes of lake basins; then a key to the irregularity of their occurrence; something of their ancestry and their changes with time. The conditions that govern the volume and composition of their water are also of interest, and lacustrine faunae are worthy of special study as showing the persistence of species characteristic of marine basins and the effect of isolation upon aquatic animals that formerly had a wider range. In this they are comparable to the forms of life on islands: indeed the similarity of these problems is noteworthy; it depends upon a relation that may be condensed into the form of a proportion — lakes are to oceans as islands are to continents. In the present paper, the latter topics will be omitted; the former suggest ample material for a long chapter.

REVIEW OF PREVIOUS TREATMENT OF THE SUBJECT. To show what has been done, as well as to point the necessity of doing more, the following abstracts are given from various works on physical geography and geology and from special papers.

It must be borne in mind that these notes refer chiefly to classification of basins, and give imperfect indication of how far geographic or statistic descriptions are carried; from the casual mention of the subject given in authoritative geological text books, it is evident that it cannot be considered geological. In addition to the general references given here, others of a more special kind will be found farther on: for access to many of the latter I am indebted to Professor J. D. Whitney's kindness in allowing me to use his library. It has been deemed advisable to include a few titles seen only in reviews.

Somerville, Physical Geography: American edition, 1849, p. 245, "The hollows formed on the surface of the earth by the ground rising or sinking, earthquakes, streams of lava, craters of extinct volcanoes, the intersection of strata, and those that occur along the edge of the different formations, are generally filled with water, and constitute systems of lakes, some salt and some fresh. Many of the former may be remnants of an ancient ocean left in the depressions of its bed during its retreat as the continent arose:" p. 246, supply of water; more lakes in high than in low latitudes on account of difference in evaporation; in Europe, one system of lakes from Scotland to Russia ("Ladoga and Onega occupy transverse rents . . . . across the paleozoic strata"); a second system from the Pyrenees along the mountains to Asia and the Caspian; in Italy, lakes in craters. Many lakes are mentioned, but their description is statistical and unsystematic.

Von Klöden, Handbuch der Erdkunde, 3 v., Berlin, 1859-62. Lake basins (i. 405) are bowl-shaped hollows in a horizontal surface, extinct craters, or the lower parts of longitudinal or cross valleys: followed by much statistical description and extended tables of altitude, depth, etc: v. Klöden also prepared the Verzeichniss von Landsee'n mit Angabe ihrer Höhenlage, Ausdehnung und Tiefe, for Behm's Geogr. Jahrbuch, i, 1866, 281; but gave no classification.

Herschel, Physical Geography, Edinburgh, 1862, p. 119, defines basin; lakes may be with or without outlet; p. 123, upheaval will form basins; if violent as in Alps, mountain lakes, less violent in Finland, etc.; occasionally created by accident, as by volcanic lava-streams.

Ramsay, 1859-1862, underrates certain possible causes and gives too great importance to glacial erosion: see p. 336.

Desor, 1860-1865, greatly exaggerates violent and orographic causes: see p. 328.

Lyell, in his Elements and Principles of Geology and Antiquity of Man, describes orographic, warped valley, earthquake, glacial erosion, ice barrier, moraine, delta and river-silt barrier lakes; in the latter work he discusses the origin of lakes by glacial erosion concluding that orographic change is more effective than ice action. These descriptions are, however, scattered through his volumes, as lakes are not considered objectively but only in their geological relations.

Boccardo, Fisica del Globo, Genova, 1868, makes no classification, although entering voluminously into other departments of physical geography.

E. Reclus, La Terre, 2 v., Paris, 1877. Lakes are formed from land-slides (i. 522), they are common in northern countries (526—) in mountains (529—, the old exaggerated measures of the depth of Lake Brienz are corrected): Desor's classes are adopted (533), moraines (534), old river beds (563) and swamps (564) are referred to. Much excellent description and many references to original authorities, but insufficient classification and explanation.

J. Young, Physical Geography, New York, 1873. More variety than usual, but too condensed. P. 166. First, basins formed (a) in superficial accumulations, (1) by irregular deposit of confluent mounds of sand, etc., (2) morainic mounds; (b) in valleys obstructed by (1), glaciers (2) moraines, (3) alluvial gravels, (4) lava flows, (5) lakes of overflow; (c) behind sand-bars on coasts. Second, in rock basins formed or deepened (a) by glacial erosion, (b) by subsidence, when strata underneath have been dissolved out, or by earthquakes, (c) by elevation, as closing the mouth of a valley, (d) on a plateau. A number of good examples given and glacial erosion briefly discussed; composition of water, ancient lakes, and filling up of lakes are mentioned.

Ansted. Physical Geography, London, 1871, p. 176. Definition imperfect: a river held back by some irremovable obstacle, a river flowing across an uneven plain. Sometimes, where lakes are below sea-level, the former presence of the ocean is implied and there has been an interruption of continuity: salt lakes are balanced between supply and evaporation. Lagoons along the sea-coast. "Such are the varieties of lakes." Much purely geographic description follows.

Wallace. On Lakes and Lake Regions, Proceedings of the American Association, 1871, XIX, 182-185. First, primitive or innate basins, the result of (a) depression of strata, (b) faults, (c) erosions (not farther explained), (d) clefts; second, proximate or incidental, the effect of (a) glacial action, (b) subsequent eruptions, (c) drift, (d) damming by drift-wood, (e) beaver dams, (f) irregular subsidence or elevation. There are areas of numerous lakes, but it is not well determined why — perhaps because they are new lands; and areas of no lakes, where the barriers are worn down. In composition: fresh, having overflow, in northern regions that have been glaciated, but relation of effects to cause has not been clearly set forth; salt, in dry regions, no overflow. No examples by name. This paper as published seems too condensed to do justice to its author.

Jukes and A. Geikie. Manual of Geology, Edinburgh, 1872, p. 460. Most lakes are in rock-basins, and in northern parts of the globe, in greatly denuded regions; basins are of recent origin. They are found first, behind barriers of superficial accumulations, (a) gravel from side stream, (b) land slips, (c) moraines, (d) irregular deposits of detritus as (1) among morainal mounds, (2) among dunes, (3) on drift or boulder clay, (4) between volcanic cones, (5) in craters, *maare*, (6) lava dams. Second, in rock basins formed (a) by depression of upper part of valleys (suggested but not admitted), (b) by local subsidence as Dead Sea and perhaps lakes of Central Africa, (c) by sinks, as turloughs of Galway, (d) by ice erosion, for the vast majority of lakes in the Northern hemisphere.

A. Geikie. Elementary lessons in Physical Geography, London, 1879, 265. Less explicit than the above, being adapted to younger students. Lakes occur in inequalities in the land surface; many in northern Europe and America; basins in rock, in superficial detritus, behind moraines, in depressions on table-lands, many of these being salt, maritime lagoons, sinks. Examples of size, depth temperature, and effect on rivers.

Huxley. Physiography, New York, 1878. Lakes are given only a short geographic description.

Dana, in his Text-book and Manual of Geology, treats lakes only incidentally: in the latter, edition 1880, p. 842, is a list of nine causes of lake-basins, in half a page, under the heading "Effects referred to their Causes."

Peschel. Physische Erdkunde, edited by Leipoldt, 2 v. Leipzig, 1879-1880, ii, p. 313. The chapter on Lakes is taken with few changes from "Die Entwicklungsgeschichte der stehenden Wasser auf der Erde," first published in "Das Ausland" for 1875. Shore lagoons (I, 433, II, 313); "Relicten-Seen," showing by their fauna a former connection with the ocean (314—); salinity does not necessarily imply oceanic origin (314). Unlike these are the lakes never connected with the ocean, including sinks on limestone, gypsum and salt beds (324), on faults, in craters (I, 217), behind ice-dams (326), held by land slides, fan-deltas, moraines (327), kept empty by ice-masses, while surrounding surface was deposited (327), orographic, quoting Desor and even copying his greatly exaggerated figures (328). We may note (I, 483) that Peschel considers the Norwegian fjords and the Italian lakes as submerged valleys, kept empty by glacial occupation (479), and shallowed at mouth by sea deposits eroded from neighboring shores (482). Most attention is given to the Relicten-Seen. I have taken a number of examples from this work.

Hochstetter, in Hann, Hochstetter und Pokorny's Allgemeine Erdkunde, Prag, 1881, p. 332. Lake barriers are formed by hard rocks resisting erosion, up-faults, lifting of valley bottom in mountain making, land slides, moraines, glaciers. Lakes may be classed (p. 334) according to their formation as (*a*) erosion lakes (not further described); (*b*) barrier lakes, from (1) land slides, (2) moraines, (3) dunes; (*c*) structural lakes, in (1) *cluses*, (2) *combes*, (3) troughs; (*d*) sink-holes; (*e*) volcanic lakes, in (1) ring-walls with crater in the middle, (2) craters, (3) *maare* (explosion craters?), (4) subsided volcanic regions. On p. 335, fjords are considered as river-cut valleys, where glaciers have done little except in preventing their filling long ago with sediment, and the Italian lakes are classed as "Binnenfjorden."

CLASSES OF LAKE-BASINS. Lakes occupy depressions that may be grouped, according to the way in which they are formed, in three classes: first, Construction or Orographic basins, caused by a movement of the earth's surface; second, Destruction or Erosion basins, formed by the local removal of material; third, Obstruction, Barrier or Enclosure basins, produced by irregular accumulation of material that acts as a barrier or encloses a hollow.

Under these main classes, a great variety of agents serves as a basis for further division into species; and these species may sometimes be again divided into varieties distinguished from their fellows by some slight change of cause, and into hybrids or basins of complex origin. We shall note that certain species are much more prolific than others; for example, drift-lakes, which probably outnumber those from all other causes combined. On the other hand, some species include lakes altogether insignificant in number or size, as glacial-lakes, held by barriers of ice, but these deserve attention as in times lately past they were of much importance. Ponds must not be neglected, for they gain from their common occurrence a value not warranted by their small area; and from being frequently met in the field of our observation they give many opportunities for analysis and classification. Size and variety are therefore to be considered only secondarily; difference in origin is the prime object of study.

A. 1. *Great Basins.* When the growth of confluent or neighboring mountain-chains encloses a less disturbed area within their circuit so as to leave no low drainage exit to the sea, the basin thus formed will be taken possession of by a lake of a size proportionate to the rainfall of the region and the area drained by its rivers. This may be called a Great Basin Lake.

If plenty of water be furnished, it will rise to the lowest point of the surrounding rim and there overflow, so attaining its greatest volume. Certain ones, as the Great Lakes of Central Africa which probably belong here, are the only examples of this species now to be found where the water supply is sufficient to cause overflow and keep the lakes fresh: the Nyanzas are held permanently up to their outlets, so far as explorers have yet reported, by the heavy equatorial rains, but Tanganyika is on the verge of becoming salt; its waters are faintly brackish, and its outlet, the Lukuga, that flowed westward into an upper arm of the Congo, when seen by Cameron in 1874,[1] was found by Stanley to be only a series of stagnant, reedy pools. We need not however adopt Stanley's catastrophic theory to explain the change.[2] In this stage Great Basin Lakes are deep and generally have well marked shores, but they are now rare: the basins are usually cut off from a direct and plentiful supply of oceanic moisture by the mountains that enclose them, and in the present relation between our ocean-area and the sun's heat, evaporation from the extended surface of great lakes generally equals their moderate rain and river supply before the maximum volume is attained, and no overflow is then possible. An area is taken so that supply and loss are equal, and as there is then no way of carrying off the saline matter brought in solution by the streams, it remains and accumulates, and the water turns brackish or salt.

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[1] Cameron, Across Africa, London, 1877, 302.

[2] Stanley, Through the Dark Continent, II, 45, 31, 50. Thomson, To the Central African Lakes and back, 1881, II, 62, 71.

The interior basins have thus lost, through the recent general change toward a dryer climate,[1] the great bodies of water with which they were largely covered during modern geological times; their lakes have been reduced to small dimensions or have quite disappeared, leaving salt or alkaline deposits in their place. When near extinction, they are very shallow compared to their surface measures, their shape is irregularly oval, the shore-line is ill-defined and shifts with the seasons, and their salinity may be near or at saturation. At certain elevations above their level, are terraces or benches marking old shore-lines that were maintained for some time by a balance of supply and loss, pauses in the dwindling away of the lake; the highest of these generally shows the level of overflow, and by following around its circuit the outlet may be discovered.

Great Salt Lake is an example of the species in its ordinary, reduced condition. In the Great Basin of Utah and Nevada there are two principal areas of depression; an eastern, bordering the Wahsatch Mountains, and a western, at the foot of the Sierra Nevada, with straggling north and south ranges between them, and it is only here that an approach to definite knowledge has been gained of the early area of lakes of this class. Near Salt Lake City the terraces of earlier shore-lines have long been observed, the highest of which stands in remarkable distinctness over nine hundred feet above the present lake; and recently this has been traced with considerable care around the greater part of its course, and to the north a probable outlet into Snake River has been discovered. To the fine sheet of water, at whose margin this high terrace was formed, the name of Lake Bonneville has been given;[1] it occupied the eastern depression of the Great Basin, and was over two hundred miles long, north and south, and one hundred broad; in depth it was probably over twelve hundred feet. Its shore contoured irregularly around the mountain boundaries, and from its surface rose islands to a height of several thousand feet. A similar lake, named Lahontan,[2] existed at the same time in the western depression, with an outlet probably southward into the Colorado.

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[1] J. D. Whitney, Climatic Changes of Later Geological Times, Cambridge, 1882.

The drying up of these lakes, a process of many thousands of years, is now much nearer its final stage than its beginning. Great Salt Lake is the only considerable remnant of Bonneville, of whose volume it is now less than a hundredth part, being in depth only fifty feet. Lahontan, whose surface was greatly broken by the western Basin Ranges, is reduced to several independent salt lakes, Carson, Humboldt, Walker's, Winnemucca and Pyramid, besides some shallow "sinks" that contain water during only part of the year.

Bonneville and Lahontan were the last of a series of great lakes that have been enclosed by the ranges of our Cordilleras since the beginning of Tertiary times.[3] They successively lasted long enough to receive great quantities of sediment from the surrounding mountains, and some of these deposits are now famous for the fossils they have preserved. Their disappearance was brought about by their filling up, by a tilting of their basins, by the growth of new mountain boundaries, or by the wearing down of their outlets; and possibly early periods of dessication had a share in producing these changes. Great Salt Lake is more distinctly than any other the direct descendant of its greater freshwater ancestor, and the well marked terraces at its former levels, the extreme flatness of its shores and the indecision of its boundary, the exceedingly small depth ratio and the high degree of salinity, all combine to make it a perfect example of its species.

The other Great Basins of the present time may be rapidly reviewed: it will be noticed that their lakes are now greatly diminished in size or altogether evaporated, although the basin remains. The plateau of Mexico contains several[1]; the interior of the Argentine Republic,[2] more; the Kalahari Desert in South Africa retains Lake Ngami besides many small pools and dry salt-pans.[3] Lake Tchad,[4] on the northern side of Soudan near the Sahara, is presumably held in a basin of this kind. In Asia there are two important Great Basin regions; the Aralo-Caspian depression on the west, once connected with the Black Sea and the Arctic Ocean, and the deserts farther east between the northern and southern mountain systems.[5] Persia shows the remains of several similar lakes, now dried up.[6]

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[1] Gilbert, U. S. Geog. Surveys W. of 100th Meridian, III, 88. King, U. S. Geol. Expl. 40th. Parallel, I,·490, 525.

[2] King, I, 504.

[3] King, I, 445.

In most of these regions no single lake can claim to be the chief or sole descendant of the old occupant; many small, scattered pools often remain to share the ancestry, and these will be considered under New Land Basins (see below, C. 12); perhaps some of the examples given should be transferred to that species.

If we now suppose the disturbed areas which form the rim of the Great Basins to approach nearer one another, and the included region to take part in their motion as it diminishes in size, we shall have —

A. 2. *Mountain Trough Basins.* Although this species is connected with the preceding by insensible grades, the types at the extremes of the series are very distinct. Instead of broad and comparatively thin sheets of water, we have now rather narrow, trough-shaped lakes, with well-marked banks rising into mountain ridges, to which the axis of the lake is distinctly parallel. As a rule these basins are full to overflow, their supply being plentiful from the rainy mountain slopes, and their evaporation being restricted by the decreased ratio of surface to volume.

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[1] Humboldt, Essai politique sur la Nouvelle Espagne, 1811, I, 44.

[2] Peterman, Geogr. Mitt. Ergänz'h. 39, 1875. M. de Moussy, Confédération Argentine, 1860, I, 171.

[3] Livingston, Missionary Travels and Researches in S. Africa, 1858, 72, 75.

[4] Nachtigal, Roy. Geogr. Soc. Journ. XLVI, 1876, 396.

[5] Richthofen, China, I, 103 and pl. 2. Prejevalski, From Kulja across the Tian Shan to Lob Nor (trans. by Morgan), 1879.

[6] Blanford, Geol. Soc. Journ., XXIX, 1878, 493. Geogr. Soc. Proc. III, 1881, 79. Tietze suggests that some of the Persian plains have been formed by wind action and not as lake-beds. Wien, Jahrb. Geol., XXVII, 1877, 341.

We can give no simple examples of this species ; for as erosion and deposition both go on and probably with accelerated rate during the progress of mountain making, the enclosing ridges will be worn down as they rise, and their waste transferred to the nearest subsiding trough, and it will be rare to find a basin preserving its simple orographic form. Moreover, an excess of deposit thrown into the trough at the confluence of a lateral with the main valley frequently forms a barrier and holds the lake higher than it would otherwise stand, so that it becomes a hybrid.

Baikal, Issikul,[1] and Nicaragua so far as they are known, come under this species.

The western part of Lake Superior has a basin of this kind [2]; but the others of our Great Lakes cannot be attributed to an orographic origin, and they all owe part of their water to obstructed outlets (see C. 4). Nyassa and Tanganyika come perhaps as near this species as the first; they are decidedly elongated, and considerable mountain ranges rise in their neighborhood. Titicaca is presumably another intermediate form; although smaller and lower than it has lately been it is still nine hundred feet deep and preserves its outlet and remains fresh; Lake Aullagas, into which its Desaguadero empties, is shallow and brackish, and the sink into which this is drained is decidedly salt. The remains of many similar old lakes now appear as pampas on the Plateau of the Andes.[3] Although mentioned here, they probably belong partly under the Fan Delta and New Land species.

The southern part of the Caspian owes its depth to a pronounced orographic origin. So in the Himalaya, the valleys of Nepal and Kashmir are old orographic lake basins. In the former, no lake remains, as the barrier has been cut down and all the space between the enclosing ranges converted into great meadow-like plains; in the latter, a small part of the great meadow is unfilled, and holds Lake Walar[1] (see C. 12).

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[1] Kul (kal, gul, gueul), nor (noor), tso (cho) mean lake in the various languages of Central Asia.

[2] Foster and Whitney, Rept. on Geol. of Lake Superior, 1850, pt. II, 117. Ramsay sees no necessity for excepting this lake from a glacial origin. Phys. Geol. and Geog. Gr. Britain, 1872, 176.

[3] A. Agassiz, Proc. Amer. Acad., XI, 1876, 283.

In the Jura Mountains a number of small lakes occupy troughs formed by down-folded strata, but I cannot learn whether they may not be held back by local deposit barriers. The Lac de Joux is marked at its northeast end by a strong cross-fault.[2] The other basins hold Lacs de St. Point and des Rousses, as well as the extinct lakes of the Val de Pontarlier and the Val de Travers. A little farther south the Lac de Bourget is a good example of its kind. Guyot considers Lake Neuchatel the result of local depression.[3]

The absence of lakes in the Appalachians south of New York was noticed as a peculiarity by Lyell[4]; if any ever existed, they have long been destroyed by erosion, and when the Jura are as old as the Appalachians they will probably be as lakeless. Indeed, the rarity of small lakes distinctly referable to this species points to the complete and searching work of the erosive forces that are constantly at work cutting down valley barriers, rather than to the original absence of basins of downfolding. It is hardly possible that in a region so disordered as the Alps no trough-basins should have been formed during the extreme crushing to which the strata there have been subjected; we should better suppose that such basins were made, but were cut down at one side nearly as fast as they were folded into shape, and so were transformed into lakeless valleys. The valleys of the Rhone above Martigny, and of the Rhine above Chur, mark the sites of such attempted lakes; perhaps lakes may have existed there for a time, but as the transverse exit-valleys were cut down, the basins were opened and drained.[5] The marginal lakes of the Alps are noticed farther on.

A. 3. *Fault Basins.* These are very rare, and point to the slow growth of dislocations as well as to the careful work of water erosion, as does the preceding species. Lough Allen, near the source of the Shannon, is described by Hull,[1] as an old valley interrupted by an up-throw fault, probably of late Tertiary date; the barrier has been much worn down, but not yet entirely destroyed. The Dead Sea occupies a depression, apparently the result of a down-throw fault of considerable length, north and south[2]; the northern of the two narrow bays in which the Red Sea ends is in the prolongation of the same line, and very probably connected with it. Whether the Dead Sea derived its salt from a former connection with the Red Sea or from its inflowing streams is a question that has been much discussed, but is apart from our present consideration.

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[1] Medlicott and Blanford, Geol. India, II, 672. Drew, Jummoo and Kashmir, 207.

[2] See sheet of XI the Swiss Geol. Commission.

[3] Neuchatel Mém., III, 1845.

[4] Travels in the United States, 1845, II, 240.

[5] Rütimeyer, Thal und Seebildung, 95. Jukes, Geol. Soc. Journ., XVIII. 1862, 378.

Desor's division of orographic lakes[3] includes some basins that will here be described under other headings. His *Mulden-seen* (trough or synclinal lakes) generally come under our second species, but his *Combe-seen* (hollows on the eroded surface of a soft stratum between two parallel ridges, *i. e.*, in a longitudinal monoclinal valley) and his *Cluse-seen* (in cross valleys) need some further examination. The *combes*, if produced by ordinary erosion, cannot contain basins unless their valley line is interrupted by a deposit barrier, and then they fall under our class of obstruction lakes. The *cluses* which he seems to attribute to an actual splitting open of a cleft across the mountains, should be considered the result of erosion like the combes, and as such can as little have any basin form; basins in cross-valleys must be due to something more than simple water erosion (see Warped Valleys, p. 330, Delta-fan and Moraine Barriers, C. 1 and 3). Rütimeyer well criticises this grouping as amounting to nothing more than saying that the rock structure is the same above and below water level[4]; except for the trough basins, it certainly gives no sufficient explanation of the origin of the lakes so classed. The altogether impossible lakes represented in Desor's figures, which we are surprised to find imitated by Reclus and Peschel, might indeed be the result of splits in the earth's crust, but where can their like be found in nature? They serve best as good examples of the seriously misleading effects of exaggerated diagrams. In giving so great prominence to the direct effects of dislocation, Desor agrees with many of the older school of geologists, but he does not give sufficient proof of his statements; so far as they imply gaping fissures they are amply refuted by Ramsay,[1] but he goes too far in the disproof and excludes local disturbances from all share in making any of the Swiss lakes.

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[1] Phys. Geol. and Geog. of Ireland, 1872. 189.

[2] L. Lartet, Note sur la formation du bassin de la Mer Morte.. . . . Soc. Géol. Bull., XXII, 1865. 420. Peschel, Phys. Erdk., II. 325.

[3] Desor, De la physiognomie des Lacs Suisses, Revue Suisse, 1860. Deutung der Alpen-Seen, in Gebirgsbau der Alpen, Wiesbaden, 1865.

[4] Op. cit. 50, note.

Whitney's orographic lakes, of which Erie[2] and its companions are examples, we should call petrographic instead; they follow the outcrop of certain formations very closely, but with the exception noted above, these basins give no sign of disturbance or sinking, and seem to be simply lakes of erosion, warping and obstruction combined (C. 4).

Dislocations on fissures are generally given greater prominence than is here allowed them in the formation of lake basins, and the basin itself is often taken as evidence of the fault required to produce it. I believe more caution than is usual might be well exercised before admitting the existence of faults, which are, as Favre says, too commonly accepted as an easy way out of a difficulty. They have undoubtedly in many cases a strong influence in guiding a stream in the erosion of its valley, but on the other hand some rivers show a marked disregard of fault lines, and in no instance can a valley or lake be ascribed to a broadly open, gaping fissure, for such fissures do not exist. Plenty of authority may be found for difference of opinion on this point,[3] but we note here only one statement bearing on the subject in hand. Kinahan[4] does not claim that valleys and lakes are produced by faulting or fracturing alone, but rather by the action of erosive agents, such as streams and ice guided by previous breaks in the rock; and as evidence to support this view he instances many lake basins in Ireland that are placed where fault-lines intersect. That fissures and joints are as a rule lines of weakness, can hardly be disputed, but there are other conditions equally potent which the author neglects as much as he exaggerates the effects of faults: the very imperfect correspondence of the irregularities of Lake Conga with the fissures considered as its cause (see his plate ii) point to the overrating of their power.

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[1] Geol. Soc. Journ., XVIII, 1862, 188.

[2] Climatic Changes of later Geol. Times., 16.

[3] Among those who consider the forms of mountain and valley surface largely the direct result of disturbance and dislocation and to a less degree the effect of erosion, we may name L. v. Buch, B. Studer, Desor, and Hopkins; See also, Kjerulf, Ein Stück Geographie in Norwegen, Berlin Erdk. Zft., XIV, 1879, 144.

[4] G. H. Kinahan, Valleys and their relations to Fissures, Fractures and Faults, 1875.

A. 4. *Warped Valley Basins.* Valleys of erosion may be locally so elevated and depressed by transverse folding as to interrupt the continuous slope of their water line; the depressions will then fill up and appear as lakes. It was to this explanation as applied by Lyell to Lago Maggiore that Ramsay[1] made objection; but the objection holds good only if it be supposed that the valley sinks rigidly, in which case a depression of some twenty thousand feet would be needed in the Central Alps to cause the lakes at their southern base; but if, as Lyell points out,[2] the valley slope be changed by a folding, as is supposed in this species, the objection falls to the ground. For the Italian lakes some such folding offers a possible explanation, but it is not well proved and is not altogether necessary (see C. 3); at the northern base of the Alps the case is better made out.

There is good evidence to show that the construction of the higher Alps and the cutting of transverse valleys were well advanced toward completion before the disturbance of the northern margin of Miocene rocks began, and it is very probable that the northernmost folds of the *molasse* were the latest made. In the upper parts of the transverse valleys, any lakes that may once have been formed during the growth of the Central Alps have long since been drained by the cutting down of their barriers, for such lakes are simply transient phases in the history of the valley; near the plain, where the disturbances of mountain growth are of comparatively recent geological date, the valleys have been interrupted by the growth of folds across their course and converted for a time (of which the present epoch is a part) into marginal lakes.[1]

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[1] Ramsay, Sir Charles Lyell and the Glacial Theory of Lake Basins, Philos. Mag., xxix, 1865, 285-298.

[2] Antiquity of Man, 1873, 358.

For the Reuss, it is probable that its early course lay in continuation with the upper part of Lake Lucerne (Urner See), east of the Rigi, into the troughs of Lakes Zug and Zürich; a landslide from the Rossberg turned it westward by a longitudinal valley till it joined the Aa, and the two streams flowing northward together were converted into a lake by foldings in the neighborhood of Lucerne.[2] This last change had a marked effect on the course of the Kleine Emmen also; this stream rises north of Interlaken and has a well preserved old valley across the Plateau to the Aar at Aarburg, but now abandons its old course at Wiggern, and turns sharply round to the east, following a trough which carries it to the Reuss below Lucerne.[3]

Changes similar to these are appealed to by Favre to explain the origin of Lake Geneva [4] and by Rütimeyer to account for several of the lakes of Northern Switzerland,[5] but their arguments are more geological than can be properly introduced here.

It is objected to the above explanation that, in the case of Lake Lucerne for example,[6] the material eroded from the neighboring mountains should have long ago filled the basin; but if we accept the well-reasoned conclusions of Heim and Rütimeyer, it will be apparent that the region about the lake was eroded much into its present form before the outer post-miocene folding changed the valley into a basin.

That several of these lakes are submerged valleys of erosion is made the more probable by finding the form of their cross-section agreeing closely with that of a river trough, after a long period of lateral cutting with but little deepening has given it a flat bottom.[1] Lakes Geneva, Brienz and the upper part of Lucerne show this very well; Brienz has not, according to recent measures, the excessive depth formerly attributed to it, but is scarcely deeper than Lake Thun.[2] The lakes that probably owe at least part of their formation to the late changes on the north flank of the Alps are, beginning at the southwest, Annecy, Geneva, Thun-Brienz, Lucerne, Zug, Egeri, Wallenstadt, Constance, (Loisach, extinct), Kochel-Walchen, (Inn, extinct), Gmundner and some other smaller ones.[3]

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[1] Heim, Mechanismu der Gebirgsbildung, 1878, II, 228-230.

[2] Heim, op. cit., I. 316.

[3] Shown distinctly on the Dufour map of Switzerland, sheet VIII.

[4] Recherches Géol., I, 212.

[5] Ueber Thal- und Seebildung, 58.

[6] A. Geikie, On the Geol. Structure of some Alpine Lake-basins, Edinb. Roy. Soc. Proc., XII, 1869, 33-34.

The rarity, or indeed we may say absence, of this species of lake in other mountains is due to their age being generally much greater than that of the Alps; if they ever possessed such lakes, they have long since been filled or drained. Their absence on the southern slope of the Himalaya, which like the Alps is a young range, may be partly due to the excessive rain there, by which the barriers have been cut down as fast as they grew.

Warping of a very gentle kind has probably aided in the formation of our Great Lakes, which seem to be old broad river valleys, depressed at their head waters and obstructed at their outlets (C. 4); a similar change has been appealed to in accounting for the lakes of New Zealand,[4] and for some of those in Scotland.[5]

A. 5. *Earthquake Basins.* An unimportant but well-defined species includes those lakes made by local subsidence resulting from earthquakes. Southeastern Missouri affords several examples, formed in 1811-12, when a large area of the Mississippi Valley was shaken, and certain parts of the bottom land were depressed so as to be submerged to a small depth by river water; trees were killed by drowning, but remained standing above water for many years.[1] Lake St. Mary is the largest of these submerged tracts, now measuring thirty miles in length by five to seven in width.[2]

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[1] Heim, I, 293. Simony, Die Seen des Salzkammergutes, Wien, Akad. Wiss. Sitzungsb. Math. Naturw. Cl., IV, 1850, 542-566.

[2] Rütimeyer, op. cit. 58.

[3] Bonney, Geol. Soc. Journ., XXVII, 1871, 312; XXIX, 1873, 382.

[4] Hector, Geol. Mag., II, 1865, 377-378.

[5] Duke of Argyll, Annual Address, Geol. Scc. Journ., XXIX, 1873, p. LXX.

In India, at the mouth of the Indus, a much larger surface was submerged by the earthquakes of 1819, and a shallow sea, two thousand square miles in area, is the result.[3] During the great Calabrian earthquake of 1783 the Lago del Tolfilo, 1700, 900, and 50 feet, in its three dimensions, is said to have been formed suddenly by the opening of a great chasm, and filled by water issuing from its bottom.

Lakes formed by land-slips during earthquakes will be noticed farther on.

A. 6. *Volcanic Subsidence Basins.* Depressions found in some volcanic regions are ascribed to the settling down of the surface rocks into cavities emptied by the ejection of lava, but the connection between cause and effect is seldom closely demonstrable.

Lake Balaton (Platten See) in Hungary, fifty miles long, three to ten wide, and forty feet deep, is given as an example of this species, as its longer axis is parallel to a line of local volcanic action.[4] Lake Tuapo, in New Zealand, is probably of the same origin; it is a depression in volcanic rocks, twenty by twenty-five miles in cross measure, and is bordered by modern cones of eruption; Lake Rotorua is referred to the same cause.[5] The old supposition of the existence of volcanic rocks in the Thian Shan Range has recently been confirmed, and the Chaderkul near by is explained as an area of subsidence following their eruption.[6]

Lough Neagh, in northeastern Ireland, probably belongs here; it is a broad, shallow depression in a region of faulted volcanic rocks and is of preglacial origin.[7] Some of the larger circular lakes, Bolsena, Bracciano, and others of Central Italy, may be of the same origin.[8]

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[1] Lyell, Principles of Geology, II, 108.

[2] Humphreys and Abbott, Report on the Mississippi River, plate II.

[3] Frere, Geograph. Soc. Journ., XL, 1870, 181.

[4] Judd, Geol. Mag., III, 1876, 6.

[5] Hochstetter, New Zealand, 1867, 365, 379; Reise der Novara, I, 1864, 144.

[6] Stoliczka, Geol. Soc. Journ., XXX, 1874, 574.

[7] Hardman, On the Age and Mode of Formation of Lough Neagh, Ireland Geol. Soc. Journ., IV, 170; and Hull, Phys. Geol. and Geogr. of Ireland, 1878, 186.

[8] G. Vom Rath, Die Umgebungen des Bolsener Sees. Deutsch. Geol. Ges. Zft., XX, 1868, 265.

Judd, well known from his writings on volcanoes, is a most enthusiastic advocate of this species; he goes to the extreme of saying that, as we can demonstrate the production of rock-basins by this agency in volcanic regions, and as similar though less demonstrable movements occur in other districts, "are we not justified in accepting such movements as capable of explaining the formation of lake-basins in all cases, rather than in having recourse to a purely hypothetical cause" namely, glacial erosion?[1] Manifestly we are not in the least justified in so doing; the origin of lakes is so very manifold that nothing short of separate study for each important case will give ground for any final statement as to cause. As further evidence of the connection between volcanic action and lakes, Judd gives the following count of existing and extinct lakes in part of the volcanic region of Central France (Dept. Puy de Dôme). Crater lakes clearly formed by explosion, 18; lava-flow barriers, 3; basins among volcanic deposits or formed by local subsidence, 81; basins generally in old lines of drainage affected by changes of level, 174; total 276.[2] I cannot say how close an estimate this is, or whether, as seems probable, causes other than volcanic are neglected. It should be noted that it is as difficult to prove the subsidence of a lake-bottom as it is easy to suppose it; the points where observations should be made are as a rule inaccessible. Scrope held the opinion that lakes in old craters might be due to subsidence following the eruptive period, or resulting from the escape of the lava below by some other vent,[3] and if this be true, some examples given among the crater-lakes below should belong in this species.

There are a few cases where the production of lakes by subsidence in volcanic regions has been almost directly observed. In 1875 a hot lake was thus formed in the crater of Askja, the largest volcano of Iceland, during the progress of a neighboring eruption.[4]

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[1] Loc. cit. 11. The same volume contains in its later pages an amusing if not an instructive discussion excited by this suggestion.

[2] Loc. cit. 5.

[3] Volcanos, 222, 226.

[4] W. G. Lock, Roy. Geogr. Soc. Proc., III, 1881, 476; Geol. Mag., VIII, 1881, 212.

In the Eifel and in Auvergne there are some small lakes of this species; in the former, the Schalkenmehrener, Meerfelder and Walsdorfer Maare[1]; in the latter, the Lacs des Bordes, de l'Eclouze, de Bourdouze, etc.[2]

A. 7. *Subsidence Basins from Solution.* Volcanic eruption of the previous species may be replaced by removal in solution of more soluble strata, as salt, gypsum or limestone, below a less soluble surface covering. As the dissolved rocks are carried away, a depression is formed on the surface, and may hold a lake.

Certain small, shallow meres in the Red Marl of Cheshire have long been explained in this way, as the strata there contain much salt.[3] Similar sinking of the ground explains the small basins in the salt region of Eisleben, over gypsum rocks by Berlin and by Segeberg in Holstein,[4] and over limestone in many parts of the world. The latter are very common in a small way; they often vary with the season from full capacity to dryness, and their outlet is generally through the bottom by underground streams. In this country they are commonly known as sink-holes; in Ireland as sluggys, swallow-holes and turloughs.[5]

B. Destruction Basins include only those species in which erosion or excavation of some kind is sufficient to provide a hollow for a lake. As will be seen under the third class, this limitation excludes many species in which destructive agents have formed a trough, but where some supplementary action is necessary before a basin is completed; hence running water is not found as a cause under this division.

It is but recently that this has been fully recognized, as may be seen by examining the writings of geologists of the first half of this century.[6] Desor, the latest advocate of running water that I have found, thinks that many of the Swiss lakes were eroded by a powerful flood suddenly rushing out from the Alps and caused by their upheaval; that the size of the lakes corresponds to the drainage basins of the several floods, a relation which could not exist if the lakes were produced by local subsidence; and that while many of the lakes follow the slope of the plain, as the flood ran, Neuchatel and Bienne are parallel to the Jura because there the flood was turned by these mountains.[1] This is entirely inadmissible; water having no rigidity or tenacity can only cut a valley with continuous slope. Pot-holes, pools below water-falls and small hollows in river channels need hardly be considered exceptions to this rule.

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[1] H. v. Dechen, Rheinl. u. Westph. Ges. Verh., XVIII, 1861, 167.

[2] A. v. Lasaulx, Niederrhein Ges. Sitzungsb., XXV, 1868, 58.

[3] Hull, On the recent remarkable Subsidence of the Ground in the Salt District of Cheshire, Ireland Geol. Soc. Journ., VI, 1880-81, 87-92. See Ordnance Survey England and Wales, sheet 80. See also B. 8.

[4] Peschel, Phys. Erdk., II, 324.

[5] Kinahan, Valleys, 141.

[6] For Example, Rogers, Geol. Penna., I, 89, On the Lakes in Central New York.

B. 1. *Basins of Glacial Erosion.* It is certainly possible for glaciers to cut out rock-basins, but the number and size of the basins so excavated have been greatly exaggerated. Extreme views have been taken on this subject: on one side by those ardent glacialists who ascribe the greater number of lake basins and deep valleys of northern countries to ice erosion; on the other by those conservatives who underrate the power of an agent so long in existence, so powerful from its weight, so irresistible in its motion, and so effective as a means of comminution and transportation as was the wonderful sheet of ice that once covered so large an area about the North Atlantic.

The theory of the glacial origin of lakes was first proposed by Hind in 1855,[2] but did not attain prominence until advocated in a more general way by Ramsay in 1859 and especially in 1862.[3]

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[1] Deutung der Alpen-Seen in Gebirgsbau der Alpen, 1865, 138. Ramsay used similar arguments for a glacial origin of these lakes. J. W. Dawson considers our great lakes cut out by cold, deep ocean currents during a period of northern submergence. Canad. Nat., i, 1864, 218.

[2] H. Y. Hind, On the Origin of the Basins of the Great Lakes. Canadian Institute, Toronto, 1855. I do not know whether this was published or only read: it is referred to by Hind himself in the Geol. Soc. Journ., xx, 1864, 126, 130. See also his Report on the Assiniboine and Saskatch. Expl. Exped. Toronto, 1859, 122.

[3] Ramsay's papers are—The Old Glaciers of Switzerland and North Wales, in Peaks, Passes and Glaciers, London, 1859, 466.

On the Glacial Origin of Certain Lakes in Switzerland, etc. Geol. Soc. Journ., xviii, 1862, 185-203, and Amer. Journ. Sci., xxxv, 1863, 324.

The Excavation of the Valley of the Alps, Phil. Mag., xxiv, 1862, 377-380.

On the Erosion of Valleys and Lakes (in reply to Murchison), Philos. Mag., xxviii, 1864, 293-311.

Sir Charles Lyell and the Glacial Theory of Lake Basins, id., xxix, 1865, 285-298.

The Physical Geology and Geography of Great Britain, London, 1872, The question has been vigorously debated since then, but without much approach to an agreement, and the debate still goes on while each side claims a victory.

About the same date, de Mortillet [1] proposed a similar theory to account for the Italian lakes, but limited the work of glacia ice to the sweeping out of a preglacial alluvial filling of the basin; the origin of the basin itself and whether it was really a rock-basin or only an obstructed valley, was not discussed.

The arguments favoring these theories are derived first, from the visible action of existing glaciers; second, from the amount and arrangement of glacial drift; third, from a comparison of the topography of glaciated and non-glaciated regions; and fourth, from ignorance of any means except the supposed glacial erosion to produce certain observed effects. From a summary of these considerations,[2] we would conclude that the rate of glacial erosion differed little from that of the ordinary destructive forces acting on the same surface; that glacial drift was in large part supplied by material loosened from the bed-rock by preglacial secular disintegration; that the amount of material removed by ice action was not enough to destroy the larger preglacial features of the country or to create new ones of great size; that the erosion was greatest toward the centres of glacial dispersion where the ice acted longest, while on marginal areas of glacial action, erosion was largely replaced by deposition; that the most important effects of the glacial period upon drainage are the result of the concentration upon a smaller area of the detritus gathered from a larger area; and finally in more direct reference to the subject in hand, that where conditions of ice pressure and rock resistance were favorable, glacial erosion may have done what running water cannot do; it may have excavated rock-basins of no great depth, but sufficient to form lakes of moderate size.

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[1] G. de Mortillet. Note géologique sur .... le lac d'Iseo en Lombardie. Soc. Géol. France, Bull. XVI, 1859, 888–905. Gastaldi and de Mortillet. Sulla escavazione (affouillement) dei bacini lacustri compresi negli anfiteatri morenici. Milano, Soc. Ital. Atti, v. 1863, 240. In 1821 Venetz wrote "Combien n'est-il pas de petits lacs sur les montagnes, qui seroient probablement remplis de terre et de pierres, si jadis les glaciers ne les avoient pas nettoyés." Soc. Helv. Mém., I, 2°, 1833, 33.

[2] I hope to present at an early day the detailed statements on which this summary is based.

Admitting this final conclusion as a possibility, it remains to discover where examples of it actually occur. To demonstrate that a lake occupies a rock-basin of glacial erosion is a difficult matter; many rock-basins are produced by subsidence or folding, as already noted; many more that have been called rock-basins are really barrier basins as we shall see. The occurrence of solid rock in a lake's outlet is by no means full proof that it forms the entire barrier, although often appealed to as such. With the demonstration that a genuine rock-basin is of glacial erosion, there should come also the explanation of the localization of the excessive erosive force at the point where the lake is now found, and in this connection we may look at certain examples brought forward by various glacialists.

The first supposition is that where a glacier is thickest, there it will excavate most deeply and form a rock-basin. This seems natural enough, but I believe it rests on a misapprehension of the character of glacial motion; and it is seldom possible to adduce proof that shall be independent of the fact to be proved: the supposition is made to support itself.

Speaking of Lake Geneva, Ramsay says [1] "the enormous mass of ice . . . . . scooped out the lake most deeply where the thickness and weight of ice and consequently its grinding power were greatest," but he gives no proof to show that before the basin was scooped out, the ice was thickest where the lake now stands. Indeed there is good evidence to show that the highest part of the surface of the old glacier of the Rhone was not over Lake Geneva, but extended square across the plain in continuation of the lower bend of the upper Rhone (from Martigny to Villeneuve) and met the Jura at Chasseron, where erratics reach their greatest elevation on those mountains; it is therefore rather on this line that the lake should have been cut had its location depended on the thickness of the ice.[2]

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[1] Geol. Soc. Journ., XVIII, 1862, 195.

[2] Favre, On the Origin of the Alpine Lakes and Valleys. Phil. Mag., XXIX, 1865, 208.

Certain lakes of moderate size in north-western England are considered by Ward[1] to be deepest at points where from confluence of lateral glaciers and narrowing of the valleys, the pressure must have been greatest; he shows also that the amount of erosion required to form these lakes is very small, but he does not estimate the share of lake formation that may come from barrier deposits in the old valleys, and this cause would reduce the necessary glacial erosion still more.

Haast attributes much effect to a reaction from the terminal moraines:[2] when a strong terminal moraine is formed and consolidated by infiltration of glacial mud, its opposition to an advance of the glacier would cause the ice to press harder upon the valley bottom, and so cut out a basin. It remains to be proved, however, that the lakes he maps and describes are really in rock-basins and not simply dammed back by moraines; still more, that the glaciers made any attempt to advance over the terminal moraines where they seem to have halted contentedly so long.

According to some, lakes mark the position held for a time by the end of the ice: this implies that erosion progressed faster beneath the whole length of the ice than in the open valley below, so that when the glacier melted away, water would collect just above the junction of the two styles of erosion. For Switzerland, the evidence of this is very contradictory; the Italian lakes might seem to confirm it, but the proof that they are neither barrier lakes nor warped valleys is wanting; moreover the neighboring valleys of the Dora Riparia and Dora Baltea, which led great glaciers down from the Alps to the Plain of the Po, have no lakes at all comparable to Maggiore and its fellows.[3] On the northern slope of the Alps, the placing of most of the lakes is orographic, and quite independent of the termination of the old glaciers.[1]

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[1] Geol. Soc. Journ., XXX, 1874, 101; XXXI, 1875, 152-166.

[2] Notes on the Causes which have led to the excavation of deep Lake basins in Hard Rocks in the Southern Alps of New Zealand. Geol. Soc. Journ. XXI, 1865, 130-132, and also 133-135.

[3] Favre, loc. cit. 211. Gastaldi thinks these valleys were occupied by lakes when the glaciers melted away, but they have since been filled by alluvium. Sulla riescavazione dei bacini lacustri per opera degli antichi ghiacchiai. Milano, Soc. Ital. Mem., I, 1865, 28.

The case for Norway as stated by Helland,[2] is of much interest, but is inconclusive. In the country inland from the Christiania Fjord, he describes four successive belts of terminal moraines, behind each of which lie numerous and deep lakes. "I have visited all," he says, "and can directly demonstrate that most of them are true rock-basins":[3] and a similar relative placing of rock-basins and terminal moraines is claimed for many of the lakes along the western slope of Norway. It is to be regretted that the observations by which these lakes are known to be in rock-basins were not given with greater detail, for at present we are compelled to doubt their completeness, and consider the lakes as most largely the effect of moraine barriers. Helland mentions that there are also lakes without moraines at their lower ends, and considers these the result of a local increase of erosive power.[4]

The explanation originally given by Ramsay for Lake Neuchatel has been extended by Geikie. In its first form, it ascribed the lakes at the foot of the Jura to the lateral deflection of the highest part of the Rhone glacier on meeting this range:[5] we should expect, however, to find basins formed by a south-westward deflection, as well as by a north-eastward, but none such exist.

Deflection basins as described by Geikie[6] are the result of an "undertow" or lateral escape current formed where the ice-sheet met an obstacle which only its upper part could surmount; his examples are unfortunately all submerged off the west coast of Scotland, and it is quite impossible to say whether they are rock basins at all, or simply old submerged valleys, clogged with glacial and marine drifts. Certainly the local deepening in the North Channel between Scotland and Ireland is not necessarily entirely the result of erosion any more than the long depression across

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[1] Excepting the smaller morainal lakes about Zurich (see C. 3).

[2] Die glaciale Bildung der Fjorde und Alpenseen in Norwegen. Pogg. Ann. CXLVI, 1872, 538-562. On the Ice-Fjords of North Greenland, and on the Formation of Fjords, Lakes and Cirques in Norway and Greenland. Geol. Soc. Journ., XXXIII, 1877, 142-176.

[3] Loc. cit. 170 ; also 166.

[4] Loc. cit. 172.

[5] Ramsay, loc. cit. 195.

[6] Great Ice Age, 289—

Scotland known as the Great Glen. The North Channel may surely be partly at least the result of stratigraphic displacement, and of subsidence in a region so very volcanic. Not proven must be the verdict here.

It has been suggested[1] that lakes are formed where the valley down which the glacier advanced decreased its slope on reaching a more level country, because there would be an increase of thickness and of pressure at the point of change. Certainly many lakes are thus placed, but exceptions are equally numerous, and in many of the examples claimed as rock-basins, this important point of structure is insufficiently proved.

Local weakness of the rocks over which the ice moved may have determined many of the smaller basins, but it is as insufficient as the other suggestions in explaining many of the larger lakes. Lake Geneva is not deepest at its western end where it is cut in soft rocks, but near its eastern where it lies in hard limestones. So the marginal lakes of the Alps from Thun to Wallenstadt, are, as above noted, in hard rocks that have been recently flooded by back-water and not in the softer rocks of the plain on which their glaciers extended. Our Great Lakes generally follow limestones and softer rocks very closely, but the evidence ordinarily given to show that the basins were excavated by glaciers really proves nothing more than that they were for a time occupied by glaciers; there are many facts that lead us to suppose the greater part of these lakes lie in old valleys, clogged by drift. As suggested by Kinahan,[2] the local weakness which determined the site of a lake is the result of faults and fissures intersecting, and breaking the rock into fragments so it can easily be scraped out; this may be sometimes the case, but as a rule I believe the effect of faults to be less marked. Many of the lakes mentioned by this author may be found to be in barrier basins.

The difficulties that lie in the way of accepting a glacial origin for the larger lakes are, in addition to the insufficiency of glacial erosion, first, that the necessity for this acceptance is not proved, as many of these lakes have other and sufficient causes; second, that the distribution or location of true rock-basins is not sufficiently controlled by glacial but rather by orographic conditions.

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[1] Geikie, op. cit. 278, quoting Seue, Le Névé de Justedal et ses Glaciers. An enormously exaggerated diagram showing this supposition is given by A. Tylor, Geol. Mag., II, 1875, 438.

[2] Valleys, etc. (See our p. 329.)

In spite of this disagreement with the more pronounced glacialists, I have no intention of siding with the extreme conservatives. Glaciers have undoubtedly been important in cleaning out, more or less completely, many partly filled old lakes, so giving them a longer lease of life; they have frequently conspired with other causes, constructive, obstructive, or both, and lent their aid to the formation of a basin; and from their own exertions alone they have greatly increased the list of lakes by the addition of numerous tarns, both existing and extinct.

It may be well to name certain lakes, frequently accounted rock-basins, and refer them to the species to which we consider them as properly belonging; but the difficulty here arises from the almost universal complexity of causes by which lakes have been produced, and the impossibility of giving a quantitative estimate to the share of each. We may begin the attempt with the classic lakes of Switzerland.

Ramsay considers all the larger ones as essentially excavated by ice, on the line of preglacial valleys; most Swiss geologists give ice-action a very subordinate place. Following the latter, we would place all the northern marginal lakes under the Warped Valley Basins, (p. 330), the lakes of the plain about Zurich under Moraine Barriers (C. 3), and the Italian lakes as belonging to both these species. As nearly all these lakes are drained by outlets running through valleys that are deeply silted up with alluvium, something of the present height of their water surface is pretty surely due to drift obstruction (C. 4).

Norway and Sweden[1] undoubtedly possess many true rock-basins of glacial excavation, but I question whether drift barriers may not explain the greater number of lakes there, as they do in Finland: the same remark applies to Scotland[2] and Ireland,

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[1] A. Helland, Die glaciale Bildung der Fjorde und Alpenseen in Norwegen. Pogg. Ann., CXLVI, 1872, 538–562.

[2] J. Geikie advocates a glacial origin for all the larger Scotch lakes. Great Ice Age, 1877, 267.

and still more surely to North America. The observations of Hector [1] and Logan,[2] accepted by Ramsay [3] to prove that the lakes of Canada and British America lie in rock-basins, are insufficient, as attention was not given especially to this point; the region is one of difficult exploration, and the frequent mention of drift by its explorers [4] shows how much effect may be traced to barriers when it is more studied.

Small mountain tarns of glacial origin [5] are common in the higher ranges of the world, but they are so generally due in part to morainal obstruction that it is difficult to select many examples coming fully under this species. In the Alps, there are small rock-basins, as at the Grimsel Hospice, and on the summits of many passes.[6] Coom Keagh, in a "corry" or rock hollow, and some others, are given as examples for Ireland,[7] but true rock-basins "seem to be much rarer than has been supposed," for the lakes there are most frequently dammed in by loose rocks, gravel and clay. In New Hampshire and Maine, rock-basins are observed [8] but generally a drift-barrier contributes generously to the production of the lake. Some lakes of moderate size in Wisconsin are considered the result of glacial erosion guided by local softness of the rock;[1] while they are not deeper than we may admit to be within the wearing power of ice, the description of them does not exclude the possibility of their being preglacial water valleys obstructed by drift.

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[1] Geogr. Soc. Journ., XXX, 1860, 268; Geol. Soc. Journ. XVII, 1861, 388.

[2] Geology of Canada, 1863, 6, 889.

[3] Geol. Soc. Journ., XVIII, 1862, 201.

[4] See the later reports of the Canadian Geol. Survey. Many of the smaller lakes in the region of crystalline rocks are said to occupy shallow rock-basins. G. M. Dawson, Geol. and Resources of the 49th Parallel, 1875, 22, 245.

[5] E. Hull suggests that tarn be limited to small lakes of glacial origin. On the Vestiges of Extinct Glaciers in Cumberland and Westmoreland. Edinb. Phil. Journ., XI, 1860, 31-44. See also Ward, Pop. Sci. Review, 1879.

[6] Bonney, Lakes of the Northeastern Alps and their bearing on the Glacial erosion Theory, Geol. Soc Journ., XXIX, 1873, 382; also, XXX, 1874, 479. Viollet-le-Duc, Les Lacs Supérieurs, Club Alpin Franç. Ann. I, 1874, 277-282. A. Boué considered some of these high lakes of violent plutonic origin, but gave no good proof of his view. Die Seen- und Teichbildung, Wien Akad. Sitzungsb., XLIV, 1861, 1°, 621-628.

[7] M. H. Close, On some Corries and their Rock-Basins in Kerry, Ireland, Geol. Soc. Journ., II. 1870, 236. G. H. Kinahan in chapters on the "Lake Basins of Iarconnaught" and the "Valleys of some of the Irish Lakes" in his work on Valleys states that drift barriers hold back many of the lakes but considers some as true ice-worn rock-basins; his observations are not given with sufficient detail to allow one to judge of their accuracy.

[8] C. H. Hitchcock, Geol. N. H., III, 1878, 250. Professor Hitchcock writes me that he considers Memphremagog and Connecticut Lakes in N. H., and Moosehead in Maine, as rock-basins

Other scattered examples are described in the Uinta and Humboldt Mountains of Colorado and Utah,[2] in the Pir Pinjal that encloses the Vale of Kashmir on the south,[3] and in the Eastern Himalaya.[4]

It is difficult, especially in this country, to find observations made and recorded with sufficient closeness to decide that a lake occupies a simple rock-basin and overflows at the lowest point of its rock boundary. Descriptions published more than twenty years ago seldom considered this point attentively and are consequently very inconclusive; more recently, the occurrence of ledges in place in the lake outlet has been taken as sufficient evidence to prove a rock-basin; but this is equally unsatisfactory unless definite statement of the surrounding surface and slope is given as well. Finally, the very common existence of hybrids still further complicates the question. Observations on the form of a lake's shore and the neighboring country, the presence or absence of ledges and drift and their relative areas, the depth of the lake and the character of its outlet, would be of much value; they might be compactly recorded and published in little sketch-maps Such observations are quite within reach of many who spend summer vacations in the woods of Maine, the Adirondacks or Canada, and would throw much light on a mooted question.

B. 2. *Wind Erosion Basins.* It has been suggested[5] that in regions of crystaline rocks where the progress of secular disintegration was irregular, the removal by the wind of dust arising from such weathering might sometimes produce hollows that were ater, in a more humid condition of climate, filled with water. The question for us is not so much whether this explanation is true, for given the necessary time and conditions it is very possible, but whether the process ever actually occurred. Certain small pools held in rock-basins in Mongolia[1] were first ascribed to it, but little time was given to their study, and the explanation was proposed rather as a suggestion than as a final solution of the difficulty they presented.

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[1] T. C. Chamberlain, Geol. Wisc., II, 1877, 137.

[2] King, Geol. Expl. 40th Par., I, 65, 470, 476.

[3] Drew, Jummoo and Kashmir, 1875.

[4] Sir R. Temple, The Lake Region of Sikkim, Geogr. Soc. Proc., III, 1881, 321-340.

[5] Pumpelly, The Relation of Secular Rock-disintegration to Loess, Glacial Drift and Rock-Basins. Amer. Journ. Sci., XVII, 1879, 139.

B. 3. *Solution Basins.* The removal of limestone, gypsum or salt in solution in water being independent of a stream's velocity and of gravity, may in some cases form a hollow lower than its outlet; but while this has probably aided in making many valleys and lakes, it is difficult to name any basins of which it has been the sole cause.

The carboniferous limestone of the Central Plain of Ireland contains numerous lakes, many of which follow the irregularities of the limestone among other rocks so closely as to imply that they are dependent upon its solubility; Loughs Erne (Upper and Lower), Ree and Derg, besides many smaller ones, are of this kind.[2] How completely they are dependent upon solution, it is difficult to say, as the country in which they stand has been glaciated and contains much drift which may well complicate their origin.

The efficacy of the solvent power of water to produce lakes was recognized by Playfair, the pools in the marls of Cheshire serving as examples: he saw also the difficulty of forming lakes by other kinds of erosion, and in the case of Lake Geneva suggested that its basin might have been dissolved out of a great deposit of salt, of which some remains are still to be found at Bex, a little above the lake.[3] A similar cause has been surmised as an aid in forming our Great Lakes. Sink-hole lakes, related to this species, are described later.

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[1] Pumpelly, Geol. Researches in China, Mongolia and Japan, 72, 73. Minute examples, five feet in diameter, are described by Ormerod, On the Rock-Basins in the Granite of the Dartmoor District, Devonshire. Geol. Soc. Journ., xv, 1859, 16-23.

[2] Hull, Phys. Geol. and Geog. of Ireland, 198.

[3] Illustrations of the Huttonian Theory, 1802, 364.

B. 4. *Pit Crater Basins*, *Maare.* Certain peculiar lakes in volcanic regions are characterized by a nearly circular form, and an abrupt depression of their basins below the surrounding general level; the enclosing rocks are not always volcanic, and sometimes there is scarcely a trace of materials that can have been ejected from the cavity: certain examples have a more or less complete wall of fragments around their rim, and in others this is quite wanting. Some observers take these to be the result of explosive eruption by which the ejected fragments were so finely broken and scattered over so large an area that they cannot now be identified; for evidence of this they point to the violent action known in some volcanoes, by which their form is greatly and quickly altered from a cone to a broadly open crater.[1] Others consider them the effect of subsidence either within an old crater-ring, or in the neighborhood of volcanic action (p. 333). It is difficult to make a choice here because decisive and critical observations are wanting and are indeed as a rule unattainable; as in so many other cases, either cause is possible, but it is a very difficult matter to say which one really produced the known result.

The most noted regions of recently extinct volcanic action in Europe—Auvergne and the Eifel—furnish several examples of this species. In the latter, the Laacher See (*i. e.*, Lake Lake) near the Rhine below Coblenz, is an oval cavity, a mile and a half in diameter and about two hundred feet deep; the surrounding surface is strewn with fragments from the hollow, but they do not form a distinct crater-wall enclosing it: other similar but smaller lakes, Pulver, Torf, Gemünder and Weinfelder Maare, occur in the same region.[2] In Auvergne, Tazana, Pavin, and Chauvet may be named; their rim is about at the level of the surrounding surface, and their walls show volcanic rock-layers that once apparently continued across their surface, still lying undisturbed around it:[3] no lava flows can be traced from these cavities.

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[1] Judd, Volcanoes, 1881, 174.

[2] H. v. Dechen, Geogn. Beschreibung der Vulkanreihe der Vorder-Eifel. Rheinland u.Westph. Ges. Verhandl., XVIII, 1861, 1-190, p. 163—.

[3] Scrope, Volcanos, 1862, 214–. Volcanos of Central France, 1858, 81, 143.

A. v. Lasaulx, Ueber die Seen und kesselförmigen Wasserbecken im vulkanischen Gebiete Central-Frankreichs. Niederrein Ges. Sitz'b., XXV, 1868, 56, 67; Kratere und

The evidence in favor of the origin of these Maare by violent eruption is: 1°, finding that a series of transitional forms exists between true Maare and accepted craters of eruption, which are mostly common in their neighborhood; 2°, the occurrence sometimes observed of fragments of the non-volcanic rocks in which the basins are hollowed out, among the neighboring volcanic *ejecta*; 3°, the known violence of certain volcanic eruptions above noted. On the other hand, there are cases that should better be explained by local subsidence, probably connected in some way with the neighboring volcanic eruptions because 1°, no trace of ejected material can be found; 2°, so far as the non-volcanic rock in which the basin is excavated can be seen, it does not show any marks of eruption.[1]

A peculiar example is Lake Lonar, on the trap plateau of the Deccan; a shallow salt pool at the bottom of a cavity about a mile in diameter and three or four hundred feet deep: on the north and north-east sides, the edge of the hollow is on a level with the surrounding country; elsewhere there is a rim of blocks of trap forty to one hundred feet high. The volume of the rim, however, is only about a thousandth part of the cavity; and no lava flow from it can be detected on the surrounding surface.[2]

Similar basins are found in the Azores[3] and in Central America and Mexico.[4]

C. Obstruction Basins may be separated into two families: in the first, a valley or trough, produced by constructive or destructive forces, receives a local deposit that serves as a barrier, and so completes the basin; in the second, a basin remains on the surface of a deposit, because of a lack of material to fill it, or because the irregular distribution of sediments fails to bring all points to the same level. These may be called Barrier and Enclosure Basins and are further divisible as follows.

vulkanische Seen in der Auvergne, Neues Jahrb., 1870, 460. This author is inclined to regard these lakes as the result of subsidence. See our page 335.

E. Vimont, Les lacs Pavin, de la Montsineyre et de la Godivelle, Club Alpin Franç. Ann., I, 1874, 337-349. The second named is a lava-barrier basin; the third, an ordinary crater of eruption.

[1] A. v. Lasaulx, Niederrhein Ges Sitz'b., XXV, 1868, 67.

[2] Medlicott and Blanford, Geol. of India, 1880, I, 379.

[3] Hartung, Die Azoren, Leipzig, 1860, 312. There known as "Caldeiras."

[4] Squier, Mexico, 1850, 270.

C. 1. *Fan-Delta Barrier Basins.*[1] It sometimes happens that a lateral stream carries more detritus into a valley than the main stream can carry away; the surplus then accumulates as a fan-shaped delta, highest where it enters the main valley, spreading and sloping radially across it, and driving the main stream as far as possible to the opposite side.[2] So much is frequently accomplished; but as this change narrows the main channel and quickens its current, the transporting power is thus increased, and the passage is ordinarily cut low enough to prevent the formation of a lake. The Rhone, just above St. Maurice, between Lake Geneva and Martigny, has thus been crowded close to the eastern side of its valley by a heavy delta of gravel and rock brought down a ravine from the Dent du Midi, and to which great additions were made in 1835, but no lake was formed.

Pangkong in the Himalaya, back of Kashmir, is a good example of a completed lake of this species: it is a long, narrow stretch of water between steep mountain banks, and near the point where as a river it would flow into the Shyok, a lateral stream has formed a great delta-deposit and held it back. So effectually is the barrier made that no outlet flows across it: whatever escape the lake has must be through the gravel underground, but that much of the supply is counterbalanced by evaporation is shown by the brackish taste of the water. At other points in the same valley, lateral deltas nearly succeed in breaking the continuity of of the lake.[3] Some of the high lakes of Western Tibet, between the Karakoram and the Kuen Lun, seem to be of similar origin but the amount of detritus deposited about them is so great as to make the early relations of drainage doubtful.[4]

The separation of Lake Brienz from Lake Thun is accomplished by the combined deltas of the Lütschine and Lombach, entering the warped valley basin from south and north about opposite each other: Interlaken stands on the beautiful alluvial plain thus formed.[1] Similar lateral deltas separate Lakes Sils and Silvaplana in the Engadin,[2] Lago di Mezzola from the head of Como, and Derwent Water and Bassenthwaite,[3] Crummock Water and Buttermeer in the lake district of England.[4] Returning to Switzerland, the Wallen See is cut off from Lake Zürich partly by the alluvial deposit of the Linth, as well as by orographic change; and Lake Bienne standing in the upper part of an old river valley, is left empty, while below the entrance of the Aar, the channel is silted up as far as Olten. The alluvial deposits in the flat valley of California are raised a little higher opposite the discharge of King's River from the Sierra, and in the faint depression south of this gentle delta stand Tulare lake and the swampy flats south to Kern: the first is only about forty feet deep, although 680 square miles in maximum area.[5]

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[1] Peschel names this species *Sonklar'sche Seen*, after the discoverer, as he supposes, of their origin. Phys. Erdk., II, 328. But they were understood earlier, as the notes below show.

[2] Excellent figures of such deltas are given by Drew. Geol. Soc. Journ., XXIX, 1873, 441 —.

[3] Drew, Jummoo and Kashmir, 323. Tso-Moriri is of similar origin, p. 302.

[4] Id., 331.

Lake Pepin, an enlargement of the Mississippi, is caused by the excess of deposit brought by the Chippewa; the lake is shallow from overflowing on to an open valley. The Wisconsin and Illinois rivers attempt the same kind of obstruction, but with less success; it is only at low water in the dry season that the Mississippi assumes the appearance of a lake above their points of confluence.[6]

A subspecies may include certain lakes in side valleys, held back by an excess of detritus brought by the main stream and deposited so as to raise its bed in front of the lateral branches. This seems to be the origin of Lakes Bistineau, Fentry and Cross, draining into the Arkansas River in northwestern Louisiana; they are shallow, from overflowing flat bottom lands, the first named being only fifteen or twenty feet deep, although some thirty miles long.[7] In the same way, the back water by the mouth of the Minnesota is held up by the Mississippi.

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[1] J. de Charpentier, Essai sur les Glaciers, 1841, 343, note.

[2] Heim, Die Seen des Oberengadin, Schw. Alpenclub, Jahrb., xv, 1880.

[3] Playfair, Illustrations of the Huttonian Theory, 1802, 359.

[4] Ward, Geol. Soc. Journ., xxx, 1874, 96 and map. See also Kinahan, Valleys, 116: such a double lake is known in Ireland as a "lough-a-voul" (lake of the two spots).

[5] Whitney, Auriferous Gravels of the Sierra Nevada, 2.

[6] Warren, Amer. Journ. Sci., xvi, 1878, 420.

[7] Lyell, Principles of Geology, i, 450.

Very similar lakes are found on the lower course of the Danube and are most probably of this origin, although Peschel considers them fragments of the Black Sea, cut off by the Danube delta, and consequently as affording proof that lakes once salt may be washed fresh.[1] This latter point is true enough, but is not proven by the case in question. Many examples of these lakes will be found in alluvial plains.

C. 2. *Ice Barrier Basins.* Glacial lakes are now of little importance; a few occur in the higher mountain chains, but they are trifling in size, and rank with many other species only as curiosities unless they become of disastrous importance in the valleys below, from the floods that follow a giving way of their barriers. Three subspecies are easily distinguished: first, when the advance of a glacier down a main valley closes the mouth of a lateral ravine; second, when a glacier from a side valley obstructs the main stream; third, when the great ice sheet of early quaternary times melted away so as to disclose the upper part of a valley sloping gently against it.

The Merjelen-See in Switzerland serves as the type of the first subspecies; it is held back by the Great Aletsch Glacier in a little valley behind the Eggischhorn, a favorite point of view, from which the lake below and the whole stretch of the ice stream in the main valley can be seen. Sometimes the waters find an outlet through the ice-barrier; then the slow accumulation of months rushes out in a torrent, flooding the valley of the Massa below and leaving miniature bergs broken from the glacier stranded on the rocky bottom: subsequently, another motion of the glacier closes the outlet, and the basin slowly fills again. The highest level of such a lake will be determined either by free escape across the ice, when it will have a variable maximum; or by flow over a pass at the head of its lateral valley. The latter is the case with the Merjelen-See, and level of the pass is marked by a faint terrace and by a change of color on the rocks around the shore.[2]

Although rare at present, these lakes have had a considerable importance in the past. An extinct example was early recognized by Agassiz at the Parallel Roads of Glen Roy, near Ben Nevis, in Scotland;[1] these are simply the shore-line terraces of an old ice-barrier lake, the uppermost standing at the height of the pass into the next glen, but the cause of the others is not so apparent[2]; the glacier which served as a barrier has long since disappeared with all its Scotch companions.

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[1] Phys. Erdk., II, 314.

[2] L. Agassiz, Etudes sur les glaciers, 1840, 218, 220. Lyell, Principles of Geology, I, 372; Antiquity of Man, 309.

The Mattmark See, representing the second subspecies, is in the Saas valley, between Monte Rosa and the Rhone, where the Allalin Glacier advances across the main valley bottom[3]: it differs from the preceding only in the relative position of lake and barrier, and in the lake's level always being determined by flow over the ice or its moraine. The Lac du Combal is in the same way held back by the Glacier de Miage at the southern base of Mt. Blanc. Several temporary Swiss lakes of this construction have caused great damage by bursting through their barriers. A famous case is that of the Gietroz Glacier in the valley of Bagnes south of Martigny, in 1818: the lake grew to be a mile long, seven hundred feet wide and two hundred deep. An attempt was made to drain it by cutting through the ice, and about half the water was slowly drawn off in this way; but then the barrier broke, and the rest of the lake was emptied in half an hour, causing a dreadful flood in the valley below.[4] In the Tyrol, the Vernagt glacier has many times caused disastrous floods by its inability to hold up the lake formed behind it.[5] In the Northwestern Himalaya, the upper branches of the Indus are sometimes held back in this way: a noted flood occurred in 1835; it advanced twenty-five miles an hour and was felt three hundred miles down stream, destroying all the villages on the lower plain and strewing the fields with stones, sand and mud.[6]

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[1] Agassiz, Geol. Soc. Proc. III, 1842, 331; here described as a lateral glacier closing the main valley.

[2] Lyell, Antiquity of Man, 300. A good bibliography of this old lake is given by W. Jolly in Nature, May 20, 1880, p. 68.

[3] Heliotypes of this and the Merjelen See are given in "Glaciers," by Shaler and Davis, Boston, 1881.

[4] Lyell, Principles, I, 348. Biblioth. Univ. de Genève, XXI, 1827, 227; XXII, 58; XXV, 24, etc.

[5] Sonklar, Die Oetzthaler Gebirgsgruppe, Gotha, 1860, 154. Stotter, Die Gletscher des Vernagtthales in Tirol und ihre Geschichte, Innsbruck, 1840, 15.

[6] H. Strachey, Royal Geogr. Soc. Journ., XXIII, 1853, 55. Compare Drew, Jummoo and Kashmir

Mention may here be made of the small ponds held upon the ice surface where two glaciers meet, because they are higher in the middle than at the sides. The ponds are but a few hundred feet across, and very shallow; their position is permanent but not their volume; in winter they are probably frozen solid, but in summer have an open water surface. Examples may be found on the Mer de Glace at the junction of the glaciers de Tacul and de Lechaud; on the glacier de Talèfre just below the Jardin; on the Gorner glacier, below Monte Rosa, and elsewhere.[1] The lakes described as occurring on the great glaciers of the Himalaya are probably of this kind.[2]

Lakes of the third division of this species are unknown at present because the conditions which produced them have passed away; but during the glacial period, when Northeastern America and Northwestern Europe were covered by vast sheets of ice, they must have been of common occurrence in every valley that sloped against the retreating ice front; and as having had a strong influence on the existing topography of our country, they merit attention, though only affairs of the past.

The headwaters of the Red River of the North are marked on the east and west by a series of low, irregular drift-mounds, that were formed as a terminal moraine of a lobe of the great glacier during a halt in its melting away. When the retreat was resumed, the space gradually left between the moraine and the ice front was filled with water from the melting, and as the present escape to the north was prevented, the lake rose until it overflowed a low gap at the south and ran down into the Minnesota.

After a sufficient retreat of the ice, the lake was drained northward, and left a plain of remarkably level surface, made of the fine detritus that had been washed into it. It is important to note that the old channel of discharge, even close to the outlet, is a broad, deep trough cut in the drift, and of a size proportionate to the overflow of a large lake, while its present occupant, the Minnesota, is but a small stream at its headwaters, quite lost in the great valley of its predecessor. The old lake has been well named Lake Agassiz: Lake Winnipeg is probably connected with it in some way by descent, but the precise relationship is not yet made out.[1]

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[1] L. Agassiz, Etudes sur les Glaciers, 220.

[2] Godwin-Austen. Roy. Geogr. Soc. Journ., XXXIV, 1864, 19.

Wisconsin seems to have had a similar glacial lake about Fond du Lac[2]; it is curious to find that its descendant and that of Lake Agassiz have the same derivation, physical as well as etymological, and the Fox and Rock rivers[3] are related much in the same way as the Red and the Minnesota. Northwestern Ohio, and a stretch of flat country east and west, received its surface covering of stratified clays from a great body of water, dammed on the north most probably by the retreating ice, and determined at its highest level by the elevation of certain "waste weirs" on the south.[4] The flat prairies south of Lake Michigan are of the same origin.[5] Further study of this region will give a most interesting chapter in our surface geology and physical geography. The absence of similar plains in New England must be explained by the fact that here the ice-sheet ended on ground sloping to the south, so there was no opportunity for a large body of water to collect against it: our eastern prairies are under the ocean. We have, however, in the sand-plains that are common in these eastern states, evidence of the former existence of small lakes probably of this origin at least in part (see C. 4, 13).[6] About the margin of Lake Superior there are many sand terraces marking old shores, some of which are two or three hundred feet over the present surface, and although these have not been traced all around the lake-border, they are generally taken as evidence of a former level of the whole lake. It seems safer to attribute some of them at least to local bodies of water between the lake-shore and the retreating ice: the same suggestion may have some application to the other Great Lakes as well. This explanation of the formation of plains is carried to an unwarranted extent by Belt, who considers Northern Siberia to mark the area of a former lake, dammed by the advance of Arctic ice, and applies the suggestion to many other regions as well.[1]

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[1] G. K. Warren, in U. S. Chief of Engineer's Report, 1868, 307, shows probable former area of lake, suggests glacial barrier and northern depression as its cause, and explains large size of the Minnesota valley. An abstract of a later report with maps is given in Amer. Journ. Sci., XVI, 1878, 417. N. H. Winchell, Popular Sci. Monthly, III, 1873, 295. G. M. Dawson, Geol. and Resources of the 49th Parallel, 1875, 253. W. Upham, Geol. Minn. Reports, 1879, 1880, explains and names the lake and gives many additional details, with a map of the moraines.

[2] Chamberlain, Geol. Wisc. II, 1877, 137.

[3] E. Andrews, Am. Journ. Sci., XLIII, 1869, 172.

[4] Newberry, Geol. Ohio, II, 29, 51.

[5] Winchell, Pop. Sci. Monthly, III, 1873, 295.

[6] For example, Upham, Geol. New Hampshire, III, 11, 115, etc., and maps.

C. 3. *Moraine Barrier Basins.* Lakes are often found behind the abandoned terminal moraines of old glaciers. The normal terminal moraine is dropped at the foot of its halting glacier, stretching more or less continuously across its valley in a curved line, convex downward: it is often breached by the streams that flow from under and off of the ice, so that on the melting back of the glacier no lake will appear; but again it happens that the moraine grows faster than the escaping water can carry it away; then on the retreat of the ice, a lake will form. These lakes are not very durable: the entering stream, charged with sediment, rapidly fills the hollow; the moraine is of loose texture and is readily cut down at the outlet; and when the filling and lowering processes meet, the lake is converted into a flat meadow with a stream meandering through it, and this in turn will be gradually washed away till the valley is clear again. It is in this meadow condition that many small moraine lakes are now found; a good example is seen half way up Pike's Peak,[2] and in all mountains that have suffered glaciation they are very common. The Twin Lakes in the upper valley of the Arkansas are also examples of the species[3]; the list can be made as long as desired.[4]

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[1] Geol. Soc. Journ., xxx, 1874, 490: he had earlier suggested the damming of the St. Lawrence outlet of the Great Lakes by ice.

[2] Shaler and Davis, Glaciers, plate xix.

[3] U. S. Geol. Survey of the Territories, 1873, 47; 1874, 47.

[4] Ramsay, On the Superficial Accumulations, etc., of North Wales, Geol. Soc. Journ., viii, 1852, 374.

Loch Skene and others in Scotland; Young, Geol. Soc. Journ., xx, 1864; A. Geikie, Scenery of Scotland, 1865, 81, 171, 259.

Lac de Lourdes, Pyrenees; Martins, Soc. Geol. Bull., xxv, 1867, 156.

Grad, Lacs et Reservoirs des Vosges, Club Alpin Français, Ann., iv, 1878, 496; also Soc. Géol. Bull., xxvi, 1868-69, 677-686.

On the Hohe Tatra, Carpathians; see map, Ergänzungsheft 12, Peterm. Geogr. Mittheilungen.

On the Pir Panjal; Drew, Jummoo and Kashmir, 202.

In Norway; Codrington, On the probable Glacial Origin of some Norwegian Lakes, Geol. Soc. Journ., xvi, 1860, 345-346; Helland, id., xxxiii, 1877, 170; Kjerulf, Geol. Norwegen, 1880, 45.

The Moraine Barrier lakes of Switzerland require further notice. There are many well within the mountains, of which the Achen See, south from Munich, may serve as an example[1]; but more interesting are those on the open country about Zürich — Lakes Sempach, Baldegg, Hallwyl, Zürich (nearly divided by a second moraine at its middle[2]), Greifen and Pfäffikon, as well as the extinct basins, filled by deposits of the Reuss and Thur. The moraine barriers are beautifully shown on the maps (sheets VIII, IX) of the Swiss geological Survey. Ammer, Würm,[3] Chiem and other smaller lakes in Southern Bavaria are probably of the same origin.

The lakes on the Italian slope of the Alps, opening into the Plain of the Po, all have strong moraines at their southern margins,[4] but it is difficult to say how completely these barriers account for the presence of the lakes and whether other causes may not be more important; in looking at the case more in detail, we may

In New Zealand; Haast, Geol. Soc. Journ., xxi, 1865, 130-135, and Roy. Geogr. Soc. Journ., xi, 1870, 433. Russell, N. Y. Lyceum Nat. Hist. Ann., 1876, 251. Hector, Geol. Mag., ii, 1865, 377. Locke-Travers, Geol. Soc. Journ., xxii, 1866, 204. These authors are divided as to the origin of the New Zealand lakes; two being for glacial excavation, and two for moraine barriers. Hector adds warping also.

In British Columbia; Dawson, Geol. Soc. Journ., xxxiv, 1878, 113 —. Canada Geol. Survey, Report for 1876-77, 1877-78.

In the Sierra Nevada; Whitney, Geol. Cal., i, 437.

[1] Simony, Ueber Alpenseen. Wien, Verein zur Verbreit. naturw. Kennt. Schriften, xix, 1878-79, 550. Its depth is 132 metres; not a quarter of what is sometimes given, as in Nature, Apr. 11, 1878, p. 468. Gümbel, Geog. Karte d. Königr, Bayern, bl. iv, shows it as drift-barred.

[2] Escher v. d. Linth. Ueber die Bildungsweise der Landzunge von Hurden im Zürichersee. Zürich, Naturf. Ges. Mitt., ii, 1850-52, 506; Ueber die Gegend von Zürich in der letzten Perode der Vorwelt. Zürich, 1852, map.

[3] Zittel. München, Akad. Sitz'b., iv, 1874, 259.

[4] Mortillet, Carte des anciens glaciers du versant italien des Alpes, Milano, Soc. Ital. Atti, iii, 1860, 44.

Omboni, Sul terreno erratico della Lombardia, id, ii, 1859-60, 6; also iii, 1861.

Paglia, Sulle colline di terreno erratico . . . del Lago di Garda, id, ii, 1863, 337. also vi, 1864.

E. Staudigl, Die Wahrzeichen der Eiszeit am Südrande des Gardasee's, Wien, Geol., Jahrb., xvi, 1866, 479.

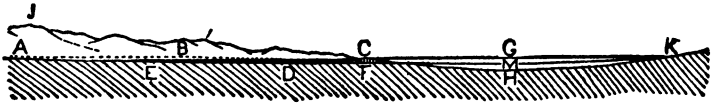
E. Desor, Paysage Morainique, Paris, 1875.

B. Martino, I ghiacchiai antichi e moderni, Torino, 1866, 80.

Rütimeyer, Pliocän und Eisperiode auf beiden Seiten der Alpen, Basel, 1876.

A glacial map of Lake Iseo is given by Geikie, Prehistoric Europe, 1881, pl. B.

first examine the possible explanations, and second, see how far these agree with the facts: it is to be regretted that the result of this inquiry must remain indeterminate as to the quantitative relations of certain causes.



The essential features of these lakes may be represented by the above diagram: there is the mountain-mass of the Alps, J C, to the north of a great depression, C H K, the valley of the Po. Eroded detritus has been carried from the former to the latter along valleys without lakes, A B C, and along valleys with lakes, A E D C. In the former there is nothing peculiar; but in the latter, how does it happen that the lakes, E D C, are still empty while the plain beyond has been filled to a level, C G K? The depth of D below C G is reported to be in Lago Maggiore more than two thousand feet.[1] The barrier F C is made to an unknown depth of deposits similar to those at G, aided by a superposed moraine of great size; it has not been shown to consist of rock.

1. We may suppose the lake-valley had the slope A B C during the filling of the depression C H K G; a subsequent folding would convert A B C into A E D C, and E D C would become a lake. This has been suggested,[2] but cannot here be so well demonstrated as for the lakes at the northern margin of the Alps. So far as it is true, it would throw the basins into the warped valley species. We say nothing of faults or fissures, for there is no sufficient evidence to show that they have been of importance in making the valleys.

2. The original line, A B C, may have been, as suggested by Ramsay, cut down to A E D C by a glacier, whose former occupation of the valley is well proven; but this requires the admission of an enormous erosive power for glacial ice, which we can-

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[1] It is very possible this depth may be exaggerated, as the measures of many other lakes have been. See Simony, loc. cit. 538.

[2] Lyell and Bonney as above, A. 4.

not allow. Undoubtedly, however, the glacier did have some effect, and in so far as it aided the formation of the lake, the basin would be classed with those of glacial erosion.

3. At an early period of the mountains' history, they may have stood higher, so that M instead of G should be the level of drainage discharge; at such a time the valley A E D F would be the result of simple river erosion. A later subsidence would bring the sea-level to E C G K, and the depression would gradually fill to that level with detritus from the higher mountains. After this an advance of glaciers from the upper valleys is supposed by de Mortillet to sweep out the sediments from the lake-basin, E D C, and in evidence of this he points to the superposition of terminal moraines at C on stratified deposits such as cover the basin G. This implies a much less powerful erosion than the preceding, and is to that extent more admissible, but I doubt whether even this amount is not too great.[1] Most assuredly all Swiss lakes of preglacial origin have had a new lease of life given them by this glacial cleaning-out, whether it was partial or perfect.

The three explanations all agree in considering the deposits H G of preglacial date, or pleiocene. The question has been raised whether the two may not be in part contemporaneous,[2] and this suggests a fourth supposition.

4. As in number 3, the erosion of A E D F was accomplished during a period of greater elevation than the present and deposits H M were then accumulated; during the latter part of the same period the old extension to F of the Alpine glaciers occurred. A subsidence then began, and keeping pace with it, the deposits M G were laid down; but E D C being occupied by ice, was preserved from filling with sediment, and on the melting of the ice was left empty (C. 13). The occurrence of glacial moraines

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[1] It should be noted that however applicable de Mortillet's theory may be to these lakes and others in Switzerland, it leaves unexplained the origin of the rock-basin itself, such as that of Lake Geneva; and also that, according to Rütimeyer (Pliocän und Eisperiode, 8) the gravels under the moraine by Como are not derived from the upper valleys of the Alps, but from the neighboring hills, and therefore give no proof that Lake Como was ever filled with detritus.

[2] Desor, Paysage Morainique, Paris, 1875, 30. Later observations make this doubtful.

upon stratified deposits at C would simply show a late advance of the ice, and bear testimony to its small erosive power; these stratified deposits, when of Alpine origin, were probably brought on the advancing ice, and washed from its foot.

That the Alps have been higher than now, as the first supposition allows, and the third and fourth suppositions require, is strongly indicated by their former glaciation. Elevation is now the main cause of the present moderate glaciation of these mountains; former greater elevation goes far towards explaining their former greater glaciation.[1] The fourth supposition has the advantage over the third of placing the extension of glaciers within this period of elevation instead of after it, and in this it agrees with the first.

As already stated, it is impossible to arrive at any quantitative estimate of the share that these several causes may have had in the result, and this want of definite conclusion is made the ground of complaint by some against this class of observational studies. We may well say on the other hand, that considering the progress made toward an explanation of these phenomena in the past hundred years, we — or our younger friends — may fairly hope for a definite conclusion in the next; and that the unsatisfactory aspect of the case at present is not its proper indefiniteness, but rather the premature assertion of final explanations without sufficient basis.

In looking at the north and south valleys of the Italian slope of the Alps, we find them in a variety of conditions: beginning at the west, there is the Dora Baltea, which led a vast glacier down from Mont Blanc to the great moraines of Ivrea, and yet is lakeless excepting for several small basins caught in the moraine (C. 13); the Sesia, lakeless; the Toce (its old course to Arona) with Lago d'Orta; the Ticino with Lago Maggiore, and several small lakes—Camobbio, Varese— between the morainal deposits; the small valleys of the Agno and Cassorate, of less size than many lakeless valleys, and yet occupied by Lago di Lugano; the Adda, with Lago di Como in its branching course, and Annone, Pusiano and others in its terminal moraine; the Bremba and

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[1] Certain geological arguments in favor of former greater elevation are presented by Medlicott, The Alps and the Himalaya, Geol. Soc. Journ., xxiv, 1868, 34.

Serio, lakeless; the Oglio with Lago d'Iseo and well-marked moraines; the Chiese and Lago d'Idro; the Sarca, with Lago di Garda, the largest of all, and projecting farthest into the plain, with a great, lobed moraine to enclose it; the Adige (= Etsch), one of the largest valleys, and yet lakeless; a great part of the glacier of the last named valley seems to have turned westward at Rovereda and joined the neighboring valley of the Sarca; farther east, there are no large valley-lakes. It is very evident from this review that no single cause for the lakes will serve; and it is noticeable that all these basins, with the exception perhaps of Idro, are connected with the great plain by open valleys, in which the alluvium or diluvium is of unknown depth, so that their rock basin structure is not proven though possible.[1] The lakes are described here because the moraines are at least to a certain extent their effective barriers, but these have been strongly aided by the conditions of our first supposition and probably equally by some modification of our fourth.

The several north and south lakes in Central New York are best placed here, but are slightly different from the preceding examples; the moraine that forms their barrier [2] was deposited by a glacial sheet that moved against instead of with the slope of their valleys, and in this they resemble the third subspecies of glacial lakes (C. 2). Cayuga lake may serve as a type of its companions, Skaneateles, Owasco, Seneca, and Canandaigua.[3] Its trough was cut by an old stream flowing from the New York and Pennsylvania plateau, northward into Lake Ontario,[4] at a time when the drainage of the region ran in channels considerably below present river levels; glacial erosion has probably smoothed and deepened it, but to suppose it entirely so formed would imply the production of a tongue of ice from the front of the old glacier, peculiar in form and remarkable in erosive power; the supposition that it is the result of down faulting or local subsidence, is negatived by the absence of disturbance in the neighboring hills; to call it a rock-basin is entirely unwarranted, for its prolongation north of the lake is across a great drift-area, without rock in place.[1] The form of the trough is different in no important particular from valleys of evident erosion in non-glaciated regions.

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[1] The conclusion reached by Gastaldi (Milano, Soc. Ital. Mem., I, 1865) in reference to this region is that there is no morainic amphitheatre without its lake (existing or extinct), just as there is no lake without its enclosing morainic amphitheatre. It should be noted that this does not involve the question of rock-basins, since the extinct lakes especially referred to about Ivrea and Rivoli have their enclosing moraines well advanced from the mountains out on the plain.

[2] Compare Spencer, Amer. Phil. Soc., XIX, 1881, 333.

[3] Oneida Lake I have not seen.

[4] Compare Carll, Second Geol. Surv. Pa., III, 1880, 330. Hall, Geol. N. Y., 4th. Distr., says these lakes are in "valleys of erosion."

The gentle escarpment of the plateau in which the lakes are sunk runs a little south of a line from Syracuse through Auburn to Canandaigua; not far north of it is a broad irregular belt of drift-hills, of peculiar form, that must be considered an old moraine remodeled by an advance of the ice over it[2]; north of Cayuga Lake these hills disappear and are replaced by a broad marsh, closely at the level of the lake; but I believe this disappearance is only apparent; the hills are pretty surely there, but are buried beneath the marsh, because being deposited in the old valley trough, their summits reached a less elevation. The marsh itself is peculiar; an alluvial flat usually occurs at the head of a lake by its inlet, not at the foot, by its outlet, as here[3]; its inverted position is to be explained by considering it of the same origin as the flat prairies of northern Ohio (C. 2); it is made of detritus washed from the melting glacier, when during its final retreat it stood near the southern shore of Lake Ontario, and held up a large body of water south of its margin. Cayuga Lake (with its companions, so far as they agree with the above suggestion) is therefore like so many others, of double origin; being due partly to a morainal barrier, and partly to a stratified drift deposit, which would carry it into the next species.

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[1] This is more distinct for Cayuga Lake than for the others, but I believe it is essentially true for all.

[2] This conclusion rests upon my own observations, confirmed by suggestions from Messrs. G. F. Wright and R. Pumpelly. Since writing the above, I find an article on the Parallel Drift-Hills of Western New York, by Dr. L. Johnson, in the N. Y. Acad. Sci., Trans., I, 1882, 77-80. The hills are considered of subglacial origin, but the lakes near by are referred to as examples of glacial erosion.

[3] The outlet of Seneca Lake which enters Cayuga at its foot cannot have deposited the marsh alluvium, for its postglacial erosion has been insignificant, as is shown by the form of the country through which it runs.

The peculiar course of the Clyde or Seneca river, the common outlet of all these lakes, is also controlled by the moraine and not by the rocks below; its variations during and after the glacial period are probably like those described by Berendt for the Weichsel in North Germany.[1] The valley of the Genesee also presents certain features worth mentioning in this connection. Between Mt. Morris and Rochester, the river follows its preglacial valley, but flows for much of this distance on an alluvial plain that closely resembles the filling of an old lake; above and below the limits named the river has cut a new channel since glacial times, giving some of the best natural sections in the state, and its old course is choked with drift.[2] In two particulars, then, the modern form of this old valley is unlike that of its fellows farther east: first, its headwaters have abandoned their old channel and made a new one; second, the lake that existed for a time in its middle course has been filled up. Evidently, therefore, the filling of the lake is the result of the cutting a new channel; one of the peculiarities of the modern Genesee depends on the other.

West of Lake Winnipeg, a number of lakes stand in valleys of the "third prairie" level, shut in by the "Coteau"; they are saline,[3] but in other respects seem very similar to the above group.

C. 4. *Drift Barrier Basins.* Besides the lakes of the previous species, whose barrier is entirely or in part referable to a terminal moraine, there are many others whose obstruction must be given the more general name of glacial or fluviatile drift; it will doubtless be possible with closer examination to recognize the special form in which the drift occurs, but as yet the subject has seldom received minute attention.

The detritus of the glacial period was deposited with much irregularity and it must often have interrupted the drainage-lines of preglacial times; we cannot doubt that the greater number of lakes in Canada, New England and the Adirondacks are of this origin, but nowhere are drift-barriers of more significance than in the region of our Great Lakes. With the exception already noted (A. 2) there is nothing to show that they are basins of subsidence or disturbance, for the rocks around their shores lie essentially horizontal; the evidence ordinarily quoted to prove their glacial origin [1] proves only their glacial occupation. Much more important than these surmises, are the observations concerning the preglacial channels by which the lake troughs were once drained. To understand the possibility of such channels, it must be borne in mind that Northeastern America has been above the sea for long geological periods, at a greater elevation than the present, especially to the north, and so subject to subaerial erosion by which valleys are made; after their formation came the glacial period, when many of the narrower valleys were filled with detritus which has not yet been washed out. The features of this "extinct geography" thus far made probable are as follows [2]: Huron, Erie and Ontario form a system of eastern drainage; Huron draining into Erie by a buried channel passing near London and Vienna, Erie emptying into the westernmost extremity of Ontario by a well-proven channel passing Cayuga and Seneca[1]; the Georgian Bay perhaps draining through Lakes Simcoe and Balsam and the River Trent into Ontario; and the united waters leaving Ontario near Oswego, passing Onondaga Lake, and perhaps following a deep channel under the Mohawk into the Hudson and down to the Atlantic by New York, though the possibility of this is questioned. Farther west, Superior drained into Green Bay, and perhaps on by the Rock River into the Mississippi; Michigan flowed out at Chicago, south and southwest, but its connection to the Ohio or Mississippi has not been traced.[2] During this condition of river drainage the lakes did not exist; their troughs were empty excepting along the deepest bottom line, with the probable exception of the orographic Lake Superior. To this it may be objected that the bottom of the more northern basins is below the supposed southern outlets; but the difficulty is fairly overcome by considering this reversed slope the result of northern subsidence which followed the glacial period: this subsidence is well proven for the Atlantic coast, and is very probable for the interior as well: this would place the basins in part under the warped valley species. There is additional and independent evidence of the former emptiness of the lake-troughs; first, in the true fjord-character of the shores of the Georgian Bay and other northern waters, the result of erosion at a time of drainage below the present water levels; the occurrence of these fjords on the northern shores points to their having formerly stood higher and later having been more depressed and overflowed than the southern; second, in the deeply buried channels of many streams or rivers running into Erie and Ontario (and probably the other lakes as well), whose rock bottom is about as low as the bottom of the lake-trough itself.[3] The position of these troughs was determined by that of the more easily eroded rocks, which they follow with remarkable closeness; and their recent conversion into lakes has been accomplished by local concentration of drift in deep, narrow valleys, where it could act effectively as a barrier; as already stated, the present lake area does not mark the maximum attained during the decline of the ice-period. St. Mary's River, Niagara and the St. Lawrence[1] are all post-glacial overflows after the obstruction by drift and the change of level by northern depression were accomplished. No more profitable field of work than the further study of this new topography can be found for the amateur observer, and in the next ten years it should yield results of great interest.

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[1] Deut. Geol. Gesell. Zft., XXXI, 1879, 14.

[2] Hall, Geol. Surv. N. Y., 4th Distr., 1843, 371, 422, gives some particulars of this region; the clogging of the old outlet by Portage formed a lake there, which was drained by the new channel from Portage to Mount Morris.

[3] Dawson, Geol. Soc. Journ., XXXI, 1875, 615.

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[1] Newberry, Geol. Ohio, I, 45; II, 72. G. J. Hinde, Canad. Journ., XV, 1877, 396.

[2] G. K. Warren, An essay concerning the important physical features exhibited in the valley of the Minnesota River and upon their signification, Washington, 1875. See also U. S. Chief of Engineers' Report, 1868, 307—, and Amer. Journ. Sci., XVI, 1878, 417.

Newberry, On the Surface Geology of the Basin of the Great Lakes, and the Valley of the Mississippi. Boston Soc. Nat. Hist., Proc., IX, 1862-63, 42; N. Y. Lyceum Nat. Hist., Ann., IX, 1870, 1; Amer Nat., IV, 1870-71, 193. Geol Ohio, I, 1873, 42—; II, 1874, 12— (including in the last, observations by Orton and Gilbert). Newberry believes also in great glacial erosion.

E. Andrews, The North American Lakes considered as chronometers of Postglacial Time, Chicago Acad. Sci., Trans., II, 1870.

N. H. Winchell, Glacial Features of Green Bay and former outlet of Lake Superior. Amer. Journ. Sci., II, 1871, 15.

E. W. Claypole, On the Preglacial Geography of the Region of the Great Lakes. Canad. Nat., VIII, 1878, 187; also Amer. Assoc., Proc., XXX, 1881.

J. F. Carll, Preglacial and postglacial drainage of Erie Co., Pa., 2d Geol. Surv. Pa., III, 1880, 331.

J. W. Spencer, Discovery of the Preglacial Outlet of the Basin of Lake Erie into that of Lake Ontario; with Notes on the Origin of our Lower Great Lakes. Amer. Phil Soc., Proc., XIX, 1881, 300; a sketch map of the old channels is given; also Amer. Assoc., Proc., XXX, 1881.

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[1] These towns on the Grand River of Canada West are not to be confused with the lakes of the same name in New York.

[2] These buried preglacial channels must not be confounded with the southern lines of overflow or "waste weirs" that were used during the glacial period, when the lake surfaces stood higher than now by two or three hundred feet.

[3] The lakes of Central New York are to be considered as occupying such old deep valleys.

While much remains to be done to complete the history of our Great Lakes, it is certainly fair to say that sufficient possibilities of origin have been pointed out to show that there is no necessity of considering them the result of glacial excavation. Lake Erie may be considered fully explained as the effect of simple subaerial erosion slightly modified by glacial action. The other lakes still present certain difficulties, but we are by no means therefore obliged to consider them the "work of the great ice plow"; it is much better to admit our present ignorance of their precise origin, and hope for fuller explanation with further study and better knowledge of their surroundings.

It has already been pointed out that rock-basins of moderate size, and presumably of glacial origin, are to be found among the numerous lakes of Northeastern America, but I believe they are far outnumbered by drift-barrier basins, and drift basins (C. 13). In Maine, most of the lakes are undoubtedly of this type[2]; in New Hampshire they are also common[3]; in the Adirondacks they seem to be very numerous[4]; in Wisconsin, Lake Winnebago would be entirely drained if the drift were cleaned out from the old channel leading to Green Bay[1]; and Winnepeg and its neighbors are described as preglacial valleys obstructed by drift.[2] The irregular forms and many islands of the latter can be due only to overflow of an uneven surface, and never to erosion by a broadly acting ice-sheet.

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[1] G. Maw (Geol. History of the N. American Lake Region, Geol. Mag., v, 1878, 456), recognizes certain new features in the St. Lawrence valley, and supposes without further evidence that the lakes above result from local post-glacial subsidence.

[2] C. E. Hamlin, On Mt. Ktaadn, Cambridge, Mus. Comp. Zoöl. Bull., VII, 1881, 192. C. H. Hitchcock in the Scientific Survey of Maine, 1862, 297 and elsewhere, notes the abundance of drift about many of the Maine lakes; ledges are mentioned in the outlets of others. G. H. Stone, Glacial Erosion in Maine, Portland, Nat. Hist. Soc., Proc., 1881.

[3] C. H. Hitchcock, Geol. N. H., III, 1878, 250.

[4] A good map but no description of cause is given by V. Colvin, Topogr. Surv. of the Adirondack Region, 1873-79.

The large lakes of Northwestern Russia are in several ways like the series of lakes in our country that stretches around from the St. Lawrence valley to the Arctic Ocean; behind them is an old worn-out mountainous country of crystalline rocks, with uneven surface though of no great height, out from which crept the ice of early quaternary times; in front of them is a broad flat region of old sedimentary strata, scarcely disturbed from their original horizontal position, and never yet subjected to rapid erosion at a considerable height above sea-level; on the former small lakes are extremely numerous, on the latter they are comparatively rare; and separating these two areas stand the large lakes, Onega and Ladoga, and their salt homologues the White Sea and the Gulf of Finland. Without asserting that local disturbance may not have had something to do with these larger depressions, I believe it will be found that they are like our great lakes in origin as in position; that they are essentially old valleys of erosion, shaped during a greater elevation of the old mountainous region, slightly modified by glacial action, and now obstructed by drift.

The very numerous lakes of Finland seem to be mostly of this character, though it is difficult to find any full description of them.[3]

We may here again refer to the presence of drift and alluvial barriers below the Swiss lakes, which so far as effective, obviate the necessity of both orographic and glacial erosion basins. All the larger lakes on the Italian slope of the Alps (except Lago d'Idro) are thus aided to an unknown extent; even the two north and south arms of Lugano are open to the valley of the Po, except for alluvial and diluvial valley-filling[1] of an undetermined depth; and it is worth noting that the cross-piece of this lake follows the outcrop of a certain series of rocks, just as longitudinal river valleys do; the southeastern arm of Como (known as Lago di Lecco) is determined by the same structural characters. In the same way, to the north of the Alps, the outlets of many lakes flow for long distances on quaternary deposits; below Lakes Neuchatel, Bienne, Thun, Zürich, Hallwyl and its neighbors, and Constance,[2] the valleys are so clogged with unstratified and stratified drift and alluvium that it is impossible to say how low the lakes would be drained were the obstructions well scoured out down to rock-bottom. To account for the deposits occurring below the lakes without filling their basins, it is not necessary to suppose any glacial erosion or postglacial subsidence, but simply that glacial ice occupied them to the exclusion of sediment, while the lower parts of the valleys were filled.[3]

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[1] T. C. Chamberlain, Geol. Wisc., II, 1877, 137.

[2] G. M. Dawson, Geol. Mag., v. 1878, 211. Maps of Lake of the Woods and Rainy Lake are given by Bigsby, Geol. Soc. Journ., VIII, 1852; X, 1854; and of the former by Dawson, Resources of the 49th Parallel, 1875, 204.

[3] G. Bohtlingk, Ein Blick auf die Diluvial-und Alluvialgebilde in südlichen Finnland. St. Petersbourg, Acad. Bull., v, 1839, 273. N. Nordenskiold, Beitrag zur Kenntniss der Schrammen in Finnland, Helsingfors, 1860.

A sufficient reason for giving so great importance to this origin of lakes, is that if the existence of so-called rock-basins can be largely disproved, one of the strongest arguments for the glacial-erosion origin of lakes is destroyed. The leading advocates of that theory lay much stress on the point that all other causes being excluded as insufficient, glacial erosion alone remains; we question very strongly whether this obstructive cause (as well, indeed, as some others) has not been too much neglected. It would be an interesting task to examine Scotland and Scandinavia with this question in mind.

Warped Valleys, Glacial Erosion Basins and Moraine Basins are very fertile in crossing with this species, and hybrids should be looked for under those headings.

C. 5. *Lava Barrier Basins.* Lava-flows sometimes perform the same office as ice-streams in forming lake-barriers, but they are vastly more enduring. Examples are not numerous; in Auvergne, Lac d'Aidat, a small basin, is so enclosed by lava from the extinct Puy de la Vache,[1] and the Lac de Chambon was formed by the eruption of volcanic cones in its valley. The Sea of Tiberias seems held back by a lava stream that entered the valley of the Jordan from the east.[2] Asia Minor will probably furnish other examples.

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[1] See maps of Swiss Geological Survey.

[2] L. Würtenberger states that the Rhine at Schaffhausen now runs in a new, post-glacial channel; Ueber die Entstehung des Schaffhauser Rheinfalls, Neues Jahrb. 1871, 582–588. The old channel would assuredly drain Lake Constance lower than its present level.

[3] This has been suggested by Escher v.d. Linth and by Desor; see Gebirgsbau; der Alpen, 136. But de Charpentier seems to be the earliest author of this idea, Annales der mines, VIII, 1834, 228.

Lake Assal, at the head of the Gulf of Aden, is shut in by a bed of lava containing several deep craters; it is about seven miles long, with a surface depressed by evaporation six hundred feet below the adjoining sea-level; its waters are very salt and there are salt deposits around it.[3] Owen's Lake, in Southern California, east of the Sierra, and some others in Utah are probably enclosed in the same way.[4] Perhaps the group of lakes in Northeastern California, drained by the Klamath, are of this origin, as the region is one of great lava-flows.

This species might be subdivided like the Ice Barrier Basins, but it is of so unusual occurrence that this is hardly necessary.

C. 6. *Sand Bar Basins* (*Etangs*). Shore lagoons, shut in behind wave and wind-formed sand bars and dunes, are common along our coast from Cape Cod to Mexico; most frequently they are open to tide water and are consequently rather arms of the sea than lakes, but considered as enclosed bodies of water of sluggish circulation and narrow outlet, they may be included in our list. There are two forms to be noted: one in which the length of the lagoon is parallel, the other in which it is at right angles to the shore. The first occur south of New York and are formed off a gently deepening shore where the heavier waves break at some distance from the beach and there drop the sand they have lifted from the bottom; as the bar shallows it grows more rapidly, and finally reaches the surface, when the winds aid the waves and pile up the bank ten or fifteen feet above water level, till it makes a continuous and secure barrier. Openings are usually preserved at certain points by the wash of tidal-currents and the outflow of rivers, and on a given shore line these breaches are prevailingly nearer one end of the bar, on account of the oblique average approach of waves and currents favoring the growth of the bar in one direction and not in the other. This is well shown as the lagoons silt up into marshes on our Carolina coast by the southward deflection of rivers that feed and drain them; still more distinctly in the great harbors on the Prussian shore of the Baltic.[1] Many of these lagoons occur at the northern end of the Caspian. The salt lakes of Bessarabia,[2] on the northwest coast of the Black Sea, were shut in on their shallow shore by sand bars and dunes, and so complete a barrier was made that the enclosed lakes lost more by evaporation than they gained from leakage and their small streams, and were on the point of extinction, when, in 1850, an especially strong storm broke down the sand barrier and overflowed the old lake area again. By this accident, an extensive salt-industry was interrupted, although the lakes after the overflow were only three to five feet deep.

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[1] Scrope, Extinct Volcanos of Central France, 92; A. v. Lasaulx, Niederrh. Ges. Sitz'b., xxv, 1868, 56.

[2] Lartet, Esquisse géol. du bassin de la Mer Morte, Soc. Géol. Bull., xxii, 1865, pl. iv.

[3] Roy. Geogr. Soc. Journ., x, 1841, 458; xii, 222.

[4] Gilbert, U. S. Surveys W. of 100 Merid., iii, 111.

Slight departures from the type are formed when an island is connected with the coast by bars at either end and a lagoon enclosed between the two; examples are given by Peschel behind the Islands Giens, Antico and Argentario on the French, Sardinian and Tuscan shores of the Mediterranean.[3] Another variation occurs at the head of the Adriatic where a long sand-bar lagoon has been divided by the growth of the Po delta.

The second subspecies depends on the closing of a submerged stream-valley by a sand bar stretching across its mouth; these are much rarer than the others. They are well seen on the southern shores of Martha's Vineyard and Nantucket, where the coast has suffered recent subsidence.[4] The triangular *étangs* of the French Biscayan coast[5] combine the forms of the two subspecies.

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[1] G. Berendt, Geol. des Kurischen Haffes . . . Erläuterung zu Sec. 2, 3, 4, der Geol. Karte v. Preussen. Königsberg, 1869. A finished study of this interesting region.

[2] G. Helmersen, Die Salzseen Bessarabiens und die Einbruch des Schwarzen Meeres in denselben in 1850. St. Petersbourg, Acad. Bull. Phys. Math., xvii, 369-397.

[3] Phys. Erdkunde, i, 446.

[4] W. Upham, The Formation of Cape Cod, Amer. Nat., 1879, 555.

[5] E. Reclus, Le Littoral de la France, Rev. des Deux Mondes, xxi, 1863, 682, and Carte de France de l'Etat majeur, sheets 170, 180, 191, 203, etc.

C. 7. *Barrier Reef Basins.* The lakes of the Everglades, in Southern Florida, owe their original enclosure from the ocean to the growth of coral reefs parallel to the present shore but farther inland.[1] The corals, aided by wave, wind and plant action, build a more or less complete barrier; the lagoon behind it becomes shallowed on either side by silt from the land and coral-sand from the reef, until all its margin becomes swampy; the water surface is raised by a narrowing of its outlet, and so a flow from the land is established, and finally its central part remains as a shallow freshwater lake, with low swampy shores.

C. 8. *River Lagoons.* (*Ox-bows: Aigues-mortes.*) Rivers of gentle slope running through a flat bottom-land of considerable breadth, are both curved and unsettled in their course; if made straight artificially, they tend to relapse into their old crooked ways; the first snag or sand-bar would divert the direct current and turn it against the bank, and so a curve would be formed that propagates its disturbance up stream as well as down. The size of such curves or meanders depends mostly on the volume and slope of the stream; as the bends become more pronounced, their necks approach each other by the caving in of the concave banks, and at last, often by the aid of overflow during floods, a short cut is made which diverts the stream from its circuitous course into a shorter and consequently steeper channel. As soon as this change is accomplished, the entrance and exit of the great bend or ox-bow begin to silt up and it is shortly transformed into a marshy lagoon. An unexpected result is the discovery that these lagoons may be deeper than the adjoining channel; this is because the stream in such a case is continually building up its bed by silt deposits; consequently the lagoon which represents an old channel will have a lower bottom than that of the present river.[2]

The lower Mississippi has many crescent-shaped lagoons of this origin in all stages of separation from the river, and of extinction by silting up[3]; some are noted in Iowa also[4]; they are common in the flood-plains of all great rivers. The Amazon is made up of so many channels and lagoons that one can hardly name them properly[1]; the Rhine by Carlsruhe gives several good examples.

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[1] L. Agassiz. Report on the Florida Reefs, Cambridge, Mus. Comp. Zoöl. Mem., VI, 1880, 32, and Leconte, Elements of Geology, 149.

[2] Warren, Amer. Journ. Sci., XVI, 1878, 422.

Humphreys and Abbott, Report on the Mississippi River, plate II.

White, Geol. Iowa, I,70.

We may note here those pools that remain in the deeper parts of an abandoned river course; they are of periodic occurrence in some of the Abyssinian branches of the Nile, where the streams evaporate in the dry season, driving all the river animals into the remaining pools.[2] In countries more permanently dried from their former raininess, the pools are now never strung together by rivers; more frequently they disappear for a time by evaporation.[3] Examples are found in the old course of the Oxus into the Caspian[4]; and along the old overflow from the Caspian to the Black Sea.[5] A few others are known on our northwestern plains.[6] The abandoned course of the Hwang Ho was for a time marked by a series of such pools, and a number of low points on the recent new course were flooded into shallow lakes.[7]

C. 9. *Landslip Barrier Basins.* Landslips often occasion an obstruction of drainage. Examples are found in countries shaken by earthquakes or in mountainous regions of heavy rainfall, and especially where these causes conspire, as in the Alps.

The Calabrian earthquake already referred to produced in this way a lake two miles long and one broad, besides many smaller pools probably of the same origin. In the Cadoric Alps, Province Belluno, Lago di Santa Croce was formed by a land-slip about A. D. 600, and Lago d'Alleghe in 1771; a little farther north, at Flattach in the Möllthal, a small lake was thus made in 1854[8] (not shown in Mayr's Alpenkarte). In the Oisans, Western Alps, a slip in 1181 made a lake ten kilometers long, known as Lac de

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[1] H. H. Smith, Brazil, the Amazons and the Coast, 1879, 93, 96, map.

[2] Baker, Nile Tribes of Abyssinia, 1867, 34.

[3] Humboldt called these lacs à chapelet, Asie Centrale, II, 138.

[4] Sievers, Peterm. Geog. Mitt., 1873, 288.

[5] Reclus, La Terre, I, 563.

[6] G. M. Dawson, Resources 49th Parallel, 230.

[7] N. Elias, Roy. Geogr. Soc. Journ., XL, 1870. Morrison, id. Proc., 1880.

[8] Peschel, Phys. Erdk., II, 828. R. Hoernes says the Lago di Santa Croce is held by a moraine, Wien, Geol. Jahrb. XXVIII, 1878, 401.

St. Laurent, and the farmers of the valley became fishermen; it existed about forty years, when the barrier gave way and the lake was drained.[1]

The southern slope of the Himalaya contains a number of small, picturesque lakes, such as Naini Tal, a favorite summer sanitarium, probably held by land-slip dams; the cause of the slip is the excessive rainfall which softens the rock and soil on the steep hill-sides.[2]

C. 10. *Beaver Dams* The beavers have contributed many small ponds, now mostly transformed to marshes or meadows, to the northern part of our country.[3] These, with the two styles or lagoons formed by coral reefs are the only species we have to note as the result of animal, organic forces; they differ very decidedly however, as the coral lagoons are entirely unintentional on the part of the reef builders, while the beaver-dams are the result of well-directed efforts to this end.

All the Obstruction Basins thus far mentioned have been of the Barrier family: the following are Enclosure Basins or hollows left from an insufficiency or irregularity of deposit.

C. 11. *Delta Basins.* Pontchartrain and the other lakes of smaller size near the mouth of the Mississippi stand in hollows left by the failure of the river to fill its delta region up to a uniform level. The river is inconstant in its course here as well as farther north, but from a different cause; here the continual accumulation of fine silt raises the bed and banks of the stream until it flows in a channel a little above the adjoining country; then a breach made during a flood-overflow may divert it to one side or the other, and in the new course so given, the raising process and the breaking away will be repeated: the various lines of flow will then be marked by rather higher deposits than the intervening spaces, as the present form of the delta where it advances into the Gulf shows very well, and finally the interlacing of old channels will enclose a faintly marked basin, very shallow, with muddy bottom and sides, and exposed to frequent invasion by the river that built its barriers. Pontchartrain with a surface of twenty by forty miles, is only twenty-seven feet deep; it lies between the Mississippi delta and that formed by the Pearl River; Lake Borgne of later beginning is not yet finished. The Holland delta-region of the Rhine and other rivers of Northwestern Germany contains many lakes and swamps large and small of this origin; the Zuyder Zee being probably a hybrid between this species and the Sand Bar Lagoons. Other examples may be found on nearly all delta districts, but are often hybrids, like the last named.[1]

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[1] Reclus, La Terre, I, 522.

[2] Ball, On the Origin of the Kumaon Lakes, India Geol. Surv. Records, XI, 1878, 174-182. Theobald, The Kumaun Lakes, id. XIII, 1880, 161-175, considers them of glacial origin. See also R. D. Oldham, On the Naini Tal Landslip, 1880, id. XIII, 1880, 277.

[3] L. H. Morgan, The North American Beaver, Philadelphia, 1868. H. Credner, Peterm Geogr. Mittheil., XV, 1869, 139.

Some swamps and lakes of the Virginia and Carolina Coast — Drummond in Dismal Swamp, Phelps and Mattamuskeet in the Great Swamp between Albemarle and Pamplico Sounds — seem to connect this species and the next: they are very shallow, the last named and largest being only four to ten feet deep with a surface fifteen by seven miles; and they occur on the highest — not in the lowest parts of their swamps, so that some have been drained and converted into good farming lands.[2]

C. 12. *New Land Basins.* The growth of deposits under a sea or lake is not such as to produce a perfect plain: there is always some irregularity in the accumulation, and although this may be slight, it fails to produce a true level by an amount sufficient to determine the placing of streams and ponds when the surface loses its continuous water covering. The manner of its conversion into dry land gives means of noting three subspecies.

First, gentle elevation without dislocation, and of amount just enough to cause emergence, brings the former sea bottom within range of observation; in this way the eastern part of Buenos Ayres has been added to South America, and its surface is marked with numerous shallow pools[3] caught at points of least deposit from their very moderate elevation and the extreme flatness of the country, the escaping drainage is sluggish, or is entirely stopped, so that the lakes are destroyed very slowly. The alluvial plain of China has several large lakes and many smaller ones that presumably belong here, or perhaps partly with the preceding species. Others occur on the steppes, east of the Ural Mountains; among these there are fresh and salt pools in the same district, the occurrence of which is explained [1] by finding, at a few feet below the surface of the flat country, a continual oozing passage of fresh water and by supposing that, as this has access to or is shut out from the pools, they are fresh or salt. Many small lakes in North Germany are of this origin, but still more are dependent on hollows of drift whose deposit was connected with the glacial period (C. 13).

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[1] See maps of deltas of Rhone, Nile, and many other rivers in Credner's Monograph on Deltas, Peterm. Geogr. Mittheil. Ergänz'h. 56, 1878.

[2] Kerr, Geol. N. Car. 18. "Dismals" and "Pocosins" are local names for these swamps.

[3] Peterm. Geogr. Mittheil. Ergänz'h. 39.

Second, an interior basin may be drained by the erosion or breaking down of its outlet; and although the surface thus gradually disclosed is level to the eye, its inequalities are detected by water seeking its own level. The ponds in the flat basin of the Theiss in Central Hungary are probably of this origin. Lake Walar in the Valley of Kashmir stands in the least-filled, middle point of the old orographic basin; it is only fourteen feet deep, though ten by six miles in size.[2]

Some insignificant ponds in the Ohio prairies may be of similar origin: here the sheet of water in which the surface strata accumulated was presumably upheld by an ice barrier, whose melting allowed a drainage outlet to be formed; very possibly other glacial conditions may have aided the production of the ponds.

Third, many interior basins have recently been laid dry by evaporation, as explained under our first species; and under this subdivision come the numerous pools of southern Russia, and the district about the Caspian and Aral.[3] Indeed, in nearly all Great Basins the existing lakes belong under this heading, for they stand as a rule upon the strata laid down by their great ancestors, and do not reach the mountain rock which encloses their basins. These lakes may be either fresh or salt; the fresh ones drain into the others, as Utah Lake by the Jordan into Great Salt. They are common in many half-desert regions; the smaller ones frequently disappear in the dry season, leaving salt or alkaline[2] incrustations on their bed; like all examples of the species they are shallow, with flat borders, and are generally less attractive than any others we have to note. Prejewalski describes one of these brackish pools in the barren, cheerless plains of Eastern Mongolia as giving anything but savory water to the caravans that stop by its margin; and another in the same country, some thirty miles in circumference, but now all evaporated and leaving in its place a bed of salt two to six feet thick, which the swans flying past mistake for a sheet of water.[1] In southern Africa there is a stream noted for changing its direction of flow with the high and low water-level of a salt lake, being therefore alternately an affluent and an effluent.[2] In South Australia the overflow of one of these lakes at high water makes its outlet run salt, but it freshens later in the season[3]; the very variable area of the Australian Lakes with the time of year caused much difficulty in the identification of sheets of water reported by different expeditions fifty years ago. Lake Sistan, into which the Helmund river of Afghanistan flows, varies so greatly in size and salinity that different explorers have reported it fresh and salt, according as they saw it near its inlet in the wet season or later in the year when it was nearly dried up.

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[1] C. Schmidt, St. Pét. Acad. Mém., xx, 1873, 4, quoting Middendorff.

[2] Drew, Jummoo and Kashmir, 166.

[3] Humboldt, Asie Centrale. II, 138, J. Spörer, Die See'nzone des Balkasch-Ala-Kul, Peterm. Geogr. Mittheil, 1868, 6Σ, etc.

The Chottes,[4] or salt depressions of Algeria, of which the proposed flooding has excited much comment, and the Bitter Lakes[5] of the Isthmus of Suez, restored to something like their original size by the opening of the Canal, are probably the combined results of elevation and evaporation.

Hybrids frequently occur between this species and the Delta Lakes.

C. 13. *Glacial Drift Basins.* Lakes of this origin have already been alluded to (C. 3, 4), and may now be described more in detail. Glacial deposits are so varied in all their characters, and so irregularly disposed in form, structure and thickness over the rock foundation on which they rest, that undrained hollows necessarily result. Such basins may be separated into subspecies according as the drift that bears them is in the form of boulder clay, moraine, kame, or sand-plain, but it is not to be expected that these subdivisions are limited by hard and fast lines; they constantly run into one another, and into the Drift Barrier Basins as well.

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[1] Mongolia, 1876 (trans. by E. D. Morgan), I, 116; II. 2.

[2] Holub, Roy. Geogr. Soc. Proc. 1880.

[3] Roy. Geogr. Soc. Journ., II, 1832, 121; VI, 1836, 434.

[4] Martins et Desor, Comptes Rendus, LXXXVIII, 1879, 268.

[5] F. de Lesseps, Sur les Lacs amers de l'isthme de Suez, Comptes Rendus, LXXVIII, 1874, 1740.

1. The surface of boulder-clay, lower till or ground-moraine of unstratified drift, is generally too well concealed by stratified drift above it to find basins determined by its form alone; but in Northern Minnesota[1] there are many lakes more dependent on this origin than any other, and doubtless others as numerous will be found in British America when the region is visited by observers having this point in view. Such lakes are small and shallow, and not of very irregular outline. In some regions the ground moraine attains an exceptional and very variable thickness in the form of drums, drumlins, whalebacks or lenticular hills (as these drift masses are called in Scotland, Ireland, New Brunswick and New England), and then, aided by other forms of detritus, they may catch ponds.[2] Some such irregularity of ground moraine combined with stratified drift is the cause of the countless ponds in the Pays de Dombes in France, northeast of Lyons,[3] and the many ponds and bogs (filz, ried, moos) on the drift from Lake Constance to Munich and beyond.[4]

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[1] W. Upham, Geol. Surv. Minn. Report for 1879.

[2] Some lakes in Northwestern Ireland are probably of this origin: see Kinahan and Close, The general glaciation of Iar-Connaught, Dublin, 1872; and Kinahan, Valleys, 110.

[3] Falsan et Chantre, Soc. Géol. Bull. xxvi, 1868, 374, and Monographie géol. des anciens glaciers . . . . du bassin du Rhone, Lyon, 1879. See Carte de France de l'Etat Majeur, sheet 159, copied in Reclus, La Terre. For the Jura, see Ch. Martins, Obs. sur l'origine glaciaire des tourbières du Jura neuchatelois; Montpellier, Acad. Mém., VIII, 1871, 6.

[4] C. W. Gümbel, Geogn. Karte des Königreichs Bayern, sheets II, III, IV, V. F. Stark, Die Bayerischen Seen und die alten Moränen, Deutsche Alpenverein Zft., 1878, 67-78, 72. Kinkelien, Senckenberg. Gesell. Bericht, 1875, 96. Zittel, München, Akad Sitz'b. IV, 1874, 259. Probst, Würtemberg. Jahresh. XXX, 1874, 59.

2. The terminal moraines of the great ice-sheets, that have attracted so much attention of late years, are essentially marked by numerous lakes, for hollows are quite as characteristic of these deposits as are hills; and irregularity, more than any positive feature, prevails wherever they are found.

The hollows are of two kinds: they may be spaces which the drift, in its uneven accumulation, failed to fill; or they may have been occupied by masses of ice while the space around was filled in by sand and gravel, and afterwards a slow melting of the ice left its place empty. When the moraine stands well above the drainage level, as in the Backbone of Cape Cod, most of the hollows will be dry because water can easily escape underground; where a less average height is reached, the numerous "bowls" or "kettles" hold fresh-water ponds. They frequently have no overflow outlet.

There are thousands of these little ponds in the various terminal moraines that curve across our country, most of which are too small to be shown on ordinary maps, for they probably average under half a mile in diameter. Before the moraine hills about them are cleared of their native forests, or when cultivated fields occupy only a portion of their surrounding slopes, they are charming features in the landscape; when the clearing about them is completed, they have lost in beauty but gained in character, as then the surface boulders scattered over the rolling mounds are brought to view. Such a view once seen is not to be forgotten: I doubt if any other species of lake is so easily recognized as this, and to its distinctness of physiognomy is due the value of these lakes and their enclosing hills, as evidence of former ice-action.[1]

The moraines and their ponds are found among the hills of Cape Cod and northward as far as Plymouth,[2] along Long Island,[3] and across New Jersey,[4] northern Pennsylvania,[5] where Rogers before noted their connection with the drift,[1] and in Ohio.[2] In Wisconsin[3] and Minnesota[4] they have lately been studied with care; and similar ponds are reported in the Coteau, the Touchwood Hills and Turtle Mountain west of Winnepeg.[5]

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[1] E. Desor, Paysage Morainique, was among the first to point out this value of their occurrence.

[2] W. Upham, The formation of Cape Cod, Amer. Nat. 1879. E. Hitchcock, Geol. Mass. 1841, II, 866;

[3] Mather, Geol. N. Y. 1st. Distr. 1843, 160.

[4] Cook, Geol. N. J. Report, 1877, Map and p. 11.

[5] A report on this part of the continental moraine is in preparation by Lewis and Wright for the Second Geol. Surv. of Penna

The morainal ponds of Europe are precisely of the same character.[6] The moraines enclosing the Italian lakes[7] all contain these hollows. Still more remarkable are the countless lakes in Northern Germany among the moraines[8] that run nearly parallel with the shore of the Baltic; "the mecklenburgish-pommersch-preussiche Höhenzuge;"[9] the drift-hills form the most conspicuous elevations of this flat country, and are throughout followed by lakes, so that their district is known as the "Seenplatte." Klöden says there are 960 lakes in Pommerania, and 1200 in Livland,[10] a similar district further northeast, but many of these seem to belong under the fourth subdivision of this species.

It is very probable that Scandinavia and Great Britain will furnish other examples of these moraine-lakes, but I can give none occurring on so large a scale as those named above. The lakes of Finland already mentioned under the heading of Drift Barrier Basins should be named here as well.

3. The mounds and ridges of gravelly, waterworn drift known as åsar, eskers or kames,[11] frequently enclose hollows or bowls holding small ponds with or without outlet; they grade into

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[1] Geol. Penna, 1858, I, 37, II, 928.

[2] Newberry, Geol. Ohio, I, 46.

[3] Chamberlain, Geol. Wisc. II, 200; III, 383; Wisc. Acad. Sci. Trans. IV, 1877, giving general map of moraines for eastern U. S.

[4] W. Upham and C. M. Terry, Geol. Minn. Reps. 1879, 1880: two valuable maps n latter. The total number of lakes in the state is estimated at 7000 to 10,000, nearly all belonging to our Drift Basin species.

[5] Geol. Surv. Territories, 1867-69, 174; 1872, 294. G. M. Dawson, Geol. Soc. Journ. XXXI, 1875, 603; Geol. and Resources 49th Parallel, 212, 222, 228.

[6] Desor, Paysage Morainique, 1875, lays much emphasis upon their occurrence, and points out their distribution: see also R. Lüddecke, Ueber Moränenseen, Inaug. Dissert, Halle, 1881.

[7] See references under C. 3.

[8] Recent observations leave little doubt of these hills being true terminal moraines of an ice sheet.

[9] Berendt, Deutsch. geol. Gesell. Zft. XXXI, 1879, 19, and pl. II and III.

[10] Handbuch der Erdkunde, I, 419.

[11] In Sweden, Ireland and Scotland: the latter name is generally adopted in this country.

basins where kames form only the barrier, and these as already noted (C. 4) constitute a large proportion of the ponds in New England. The former are seldom large enough to appear even on county maps, and they are often dry in the summer.

4. During the decline of the glacial period, many large and small lakes stood for variable periods in front of the ice (C. 2) and frequently received considerable deposits of sand and gravel, so as to appear as sand plains when the water was drained away. In northern Michigan and in Wisconsin[1] there are large plains known as "barrens" that I believe to be of this origin: smaller ones are common in New England. Again, when the ice-margin stood in the sea, the great quantity of detritus washed from it by the super and subglacial streams would tend to form a gently sloping plain immediately in front of the ice: such a one forms half of Cape Cod, south of the morainal "back-bone."[2] These flat surfaces are marked by abrupt hollows or bowls, with sides sloping five to fifteen degrees, thirty to one hundred or more feet in depth, and without inlet or outlet: the smaller, typical bowls are oval, and but a few hundred yards in diameter; they grade into much larger depressions of irregular form, with entering and outflowing streams and frequent kame-like mounds that appear as islands in the resulting ponds. The origin of these hollows is probably to be found in their occupation by isolated ice-masses while the surrounding space was filled with drift.[3] (See also C. 3.)

Ponds thus formed add greatly to the number included in this species, though in size they are insignificant. North Germany can probably give many examples.

The upper terrace plains of our larger rivers contain small ponds that may have had a similar origin: but it has been suggested that their basins were formed by a sinking of the originally even surface consequent on a slow washing or squeezing out of the lower layers. I know of no section that will decide between the two explanations.

In Eastern Massachusetts (and doubtless in many other parts of New England) the ponds generally occur on the line of a kame-series, and none of them, so far as I have been able to observe or learn, are in true rock basins. They owe their existence to ice-occupation during the deposit of the drift that is always found plentifully about them; the fact that their longer measures generally agree with the trend of glacial striae does not prove them to be the result of glacial erosion, but suggests that the valleys in which they lie and whose direction determines their longer axis, run with the general slope of the country, and consequently with the direction of motion taken by the great glacier. The ponds and the striae agree because both are the result of the same cause.

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[1] Geol. Wisc. III, 1880, 374, 385.

[2] Upham, Amer. Nat. 1879.

[3] Peschel extends this explanation to the preservation of Lake Neuchatel and its neighbors; Ueber den Ursprung der Jura- Seen, Ausland, 1868, 1005.

If a review be now made of the Glacial Erosion, Moraine and Drift Barrier, and Drift Lakes, it will be seen that much less importance is attributed to ice erosion than to its indirect effect in forming lakes by obstruction and preserving them by occupation: I consider the latter causes far more important than the former, and regard them as giving rise to much larger and more numerous basins.

C. 14. *Crater Basins.* The volcanic lakes already described, (A 6, B 4) probably have certain points in common with this species, as it is impossible in most of the examples given to determine the ratio between the effects of subsidence and of explosive eruption. Basins of volcanic subsidence may include those of considerable size, where there is no evidence to show that any material has been thrown out by eruption. Pit-crater basins are small, abruptly bordered cavities, with evidence usually of some eruption, but very possibly aided by subsidence; the type-examples have no distinct rim-wall enclosing them, but are sunk below the general surface of the surrounding country. Crater basins now to be considered have distinct walls of lava or ashes, sloping gently on the outer side and more abrupt within, and although even here subsidence of the central parts may have played an important part in the production of the basin, the more evident cause of the lakes they contain is the existence of the oval or circular barrier wall, and therefore they are placed under our third class of Obstruction Basins.

Excellent examples of these occur in the volcanic district about Rome and Naples: near the former are Albano and Nemi; near the latter, Agnano and Averno, also the Piano di Quarto and the Pianura, similar craters but not well enough enclosed to hold lakes. North of Rome there are several lakes of larger size — Bracciano, ten miles in diameter, Bolsena, six and a half miles, and some others—as to the origin of which different opinions are held: one observer considers them of explosive origin,[1] another, the result of subsidence.[2] In Auvergne, lakes in the Puys du Bar, and de St. Sandoux, the Lacs de la Godivelle, de Monsinière, and others come under this species.[3]

About Auckland, New Zealand, is a region extremely rich in lakes of this species,[4] and other volcanic countries afford further examples.[5]

Many volcanic lakes are peculiar from their contents. On the Island of Dominica there is a hot lake in a crater; at the edge its temperature is 180° F., and in the middle it boils[6]. We might mention also those craters occupied by gaseous lakes strongly charged with carbonic acid, so as to render them deadly to all animal life; such a one is known in Java; its bottom is strewn with skeletons of animals that ventured over its fatal walls.[7] Occasionally these lakes lie at great elevations, as in the crater of Toluca (Mexico), 11,490 ft., and Elbruz (Caucasus), 18,500 ft. above the sea.[8] Contrasted with these, are the isolated, oceanic crater-rings that appear just above sea-level; one side is generally breached, giving an entrance to the quiet lake-harbor within.[9]

In our own country, while there have been large areas of volcanic action, we can record few of these lakes. Thurston and Borax Lakes in the Coast Range of California are perhaps of this species; more distinct are two water-holding craters on an island in Lake Mono.[1]

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[1] Judd, The Great Crater lakes of Central Italy, Geol. Mag. II, 1875, 349-356.

[2] G. v. Rath, Deutsch. geol. Ges. Zft., XVIII, 1866, 516.

[3] A. v. Lasaulx, Niederrh. Ges. Sitz'b., XXV, 1868, 57.

[4] Heaphy, Geol. Soc. Journ. XVI, 1860, 242-252. Hochstetter, Peterm. Geog. Mittheil. 1862, map 6. Geologie von Neu Seeland, 160.

[5] F. Junghuhn, Java, II, 133, 902, describes eighteen crater lakes, of which eleven are acid, in subactive volcanoes, and seven fresh, in extinct cones. G. Hartung, Die Azoren, 311, describes and figures a number of *caldeiras*, one of which was formed in 1563.

[6] Nature, 1589, June, p. 296.

[7] Roy. Geogr. Soc. Journ. II, 1831. 60

[8] Humboldt, Cosmos, IV, 1858, 275.

[9] Deception Island, among the South Shetlands, Roy. Geogr. Soc. Journ., I, 1830. St. Paul's in the Southern Indian Ocean, Wien Geogr. Ges. Mitth. 1857, 146; A. Cazin, Club Alpin Franç. Ann. II, 1875, 542. Barren Island in the Bay of Bengal, Geol. Mag. 1879, 16.

C. 15. *Coral Island Lagoons.* The peculiar growth of coral reefs, enclosing quiet lagoons, that remained so great a puzzle till explained by Darwin, is the combined result of a limitation in the depth at which reef-building corals can live, and of the slow subsidence of the volcanic island on which they colonized. The lagoons, when enclosed from the ocean by all but a small outlet, as happens on the smaller atolls, are essentially lakes, being bodies of quiet water held apart by barriers from the general circulation: their peculiarity is less in their basin than in the narrowness of their enclosing rims. Maraki, Henuake and Taiara may be given as examples of nearly complete enclosure of the lagoon waters. With further subsidence and corresponding upward growth, these circular islands decrease in diameter and the lagoon fills up with coral sand, as in Swain's and Jarvis's Islands.[2] A less usual change in the lagoons results from an elevation of the island, so as to give it drainage downward to the ocean, and allow the salt waters to be replaced by fresh rainfall: this is presumably the explanation of the lakes on Otdia, one of the Marshall group,[2] and on Washington Island[3]: little oases of fresh water in an ocean of salt.

Having thus subdivided lakes according to their mode of formation, it remains to study their distribution and actual occurrence. This may be made the subject of a future paper.

[1] Whitney, Geol. Cal. I, 97, 453.

[2] Dana, Corals and Coral Islands, 167, 283.

[3] Smithsonian Report, 1877, 20.

Concerning Crater Lakes See Topogr. en geol. Beschrijving
van een gedeelte van – Sumatra's Westkust – Amsterdam
Stemler – 1883 – a geol. work under direction of Verbeek

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CALIFORNIA STATE DIVISION OF MINES

THE LAKES OF CALIFORNIA

Kirk Bryan

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THE LAKES OF CALIFORNIA

By William Morris Davis *

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Big Lake	50	223
Big Sage Reservoir	14	227
Blue Lake, Lassen County	17	200
Blue Lakes, Lake County	41	199, 223
Bodega Bay	63	233
Boiling Springs Lake	23	219
Bolinas Bay	59	233
Borax Lake	43	219
Bristol Lake	115	194
Britton Reservoir	20	227
Buena Vista Lake	102	224
Bumpus Hell	23	219
Butte (Bidwell) Lake	23	216
Cache Slough	52-A	223
Calaveras Reservoir	66	229
Cascade Lake	30-A	212
Castaic Lake	108	223
Chabot Reservoir	65	229
China Lake	101	193
Clear Lake, Lake County	42	195, 197, 230
Clear Lake, Modoc County	16	200
Clear Lake Reservoir, Modoc County	10	189, 227
Cliff Lake	23	215
Cluster Lakes	23	215
Crystal Spring Lake	58	229
Death Valley	96	193
Deep Spring Valley	98	193
Desolation Lake	87	211
Dollar Lake	114	214
Don Pedro Reservoir	74	229
Donner Lake	29	212
Drakes Estero	60	234
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Kern Lakes, Tulare County	93	201
Kings River Slough	89	223
Klamath River Embayment	3	231
Lindsey Lake	52	223
Loon Lake	32	209

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Bolinas B
Borax Lal
Bristol La
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Castaic La
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Cluster La
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Desolation
Dollar Lal
Don Pedro
Donner La
Drakes Est
Dry Lake,
Dry Lake,

Name	No. on map	Page
Lost Lake	18	201
Lower Klamath Lake	8	189
Lower Otay Reservoir	127	229
McCoy Tanks	117	227
McGriff Lake	46	222
Manzanita Lake	23	202
Mary Lake	47	222
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Melones Reservoir	70	227
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Merced Lake, Mariposa County	78	212
Mirror Lake	77	201, 214
Mohave Tank	116	227
Mono Lake	82	192
Monterey Bay	91	234
Moreno Reservoir	129	229
Morro Bay	105	235
Mountain Meadow Reservoir	25	227
Murphy Lake	48	222
Newport Harbor	120	235
Noyo River Embayment	36	233
Owens Lake	94	193
Owens Reservoir	72	229
Pardee Reservoir	69	227
Pear Slough	72-A	222
Pilsbury Reservoir	38	229
Pleasant Lake	31	209
Plumas Lake	45	223
Rainbow Lake	23	215
Reflection Lake	23	202
Russian River Embayment	64	233
Saline Valley	97	193
Salton Sea	118	225
San Andreas Reservoir	57	229
San Diego Bay	125	235
San Francisco Bay	55	230
San Pablo Bay	54	230
Santa Barbara Reservoir	107	229
Searles Lake	100	193
Shadow Lake	23	215
Silver Lake	35	209
Snag Lake	23	216
Soda Lake	104	197
Stone Lagoon	5	231
Stone Lake	51	223
Stony Gorge Reservoir	39	229
Suisun Bay	53	230
Swan Lake	23	215
Sweetwater Reservoir	126	229
Sycamore Slough	67	223
Tahoe Lake	30	221
Talawa Lake	2	231
Tenaya Lake	79	214
Thomas Reservoir	13	227
Thousand-island Lake	80	207
Thurston Lake	44	218
Tilden Lake	84	213
Tomales Bay	61	233
Tracy Lake	68	223
Tulare Lake	92	224
Tule Lake (Rhett Lake)	9	189
Tule Lake Reservoir	19	227
Twin Lakes, Mono County	83	213, 224
Twin Lakes, Shasta County	23	215
Van Arsdale Reservoir	37	229
Volcanic Lakes	88	214
Wilmington Lagoon	121	235
Woodward Reservoir	71	227

Part I. THE ORIGIN OF LAKES

The Forms of the Lands

The forms of the lands are determined in the main by the slow interaction of two antagonistic processes. One process, of interior origin and unsolved explanation, slowly deforms the earth's crust and

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* Professor of Physiographic Geology, Balch Graduate School of Geologic Sciences, California Institute of Technology, Pasadena, California; Professor of Geology, Emeritus, Harvard University.

makes its surface uneven. Associated with this deforming process in being of interior origin and of difficult explanation, but apparently acting independently of it, are volcanic eruptions which build up cones and domes and pour out lava flows of smaller or larger extent.

The other process, of exterior origin and simpler explanation, includes all the agencies which tend either to wear down the land surface and reduce the uneven highlands to smooth lowlands or to fill up depressed basins and convert them into smooth plains. Chief among these agencies are weathering and streaming; that is, the ordinary agencies by which rocks are distintegrated, by which valleys are deepened and widened, and by which the irregular slopes of the deformed crust are graded down or graded up to regular slopes and eventually smoothed out as plains. Associated with these familiar agencies are certain more special agencies, such as the glaciers of high mountains and the ice sheets of the Arctic and Antarctic regions; also wind action in deserts, solvent action in limestones, and wave and current action on sea and lake shores.

The fact that many unevennesses, such as mountains and highlands, exist today does not mean that the earth's history is so short that its primitive unevennesses have not yet been worn down, for all unevennesses of ancient origin were worn down ages ago. Existing mountains and highlands are of later upheaval; and although they are vastly more ancient than human history, they are young as the earth measures time; so young that they have not yet been worn down, although the agencies of weathering and streaming have very generally made good progress in carving valleys of continuous descent down their slopes. Hence it may be said in a general way that the highest mountains of today are high because they are geologically young; they represent, although already much dissected by deep-cut valleys, the latest great upheavals that the earth's crust has suffered. It should be understood, however, that geologically young mountains are historically so ancient that they antedate all human records.

The Antagonism of Lakes and Rivers

Inasmuch as rivers carve valleys of continuous down grade from head to mouth, they tend to destroy lakes; for the floor of every lake basin must have an up-grade from its deepest part to the lake outlet. The occurrence of lakes therefore suggests an imperfection or an incompleteness in the down-grading action of rivers, and hence a study of lakes must involve a search for the origin of such imperfection or incompleteness. Such study shows that basin-like depressions, large or small, have been produced in the surface of the lands by irregular deformation of the earth's crust. If the deformation is slow, the resulting basin may be filled with inwashed detritus while the deformation is in progress, and no lake will be formed; but if the deformation is more rapid, the basin will be only in part filled with detritus during its deformation, and a lake will occupy the unfilled part. Where the climate is moist such basins are water-filled to overflowing; where it is dry the basin is only in part water-filled and there is no overflow. In this case the area of the non-overflowing lake comes to be such that evaporation from its surface disposes of the inflow from the entire drainage basin: in the other case the overflow will equal the inflow minus the evaporation from the lake surface.

The study of lakes also shows that some of them occur where the land surface has been unevenly worn down by ancient glaciers, or where it has been unevenly up-built by volcanic eruptions. Moreover, certain desert regions, in the broad basins of which lakes are now small or wanting, are shown by the shore-line terraces still preserved on the basin slopes to have possessed large lakes during a moister and cooler climatic period of the geologically recent past, presumably contemporaneous with the period in which the ancient mountain glaciers and the great ice-sheets of certain continental areas attained their vast extension. All these possible causes of lake production must be investigated.

The study of lakes shows further that, whenever and wherever they are produced, the action of weathering and streaming tends, as above intimated, to destroy them, either by slowly filling their basins with inwashed detritus or by gradually cutting down their outlets and draining off their waters. Thus Lake Geneva, at the northwestern margin of the Swiss Alps, is now somewhat encroached upon by the delta that the inflowing Rhone is building at the lake head; eventually, the delta may replace the entire lake. Likewise, Lake Erie is fated to be drained away in the distant future when Niagara Falls and the rapids upstream from them are worn back sufficiently to lower the lake outlet to the level of its basin floor, which will then be laid bare as a smooth plain.

Lake basins should therefore be considered as resembling, in a smaller way, the greater unevenness of the earth's surface, because they also very generally exhibit the interaction of antagonistic processes: One set of processes producing the lake-holding basin, the other set tending to destroy the basin-holding lake. In other words, the quicker-acting but less enduring processes of lake production are, in time, overcome by the slower acting but longer enduring processes of lake destruction. Lakes are therefore, as a rule, what our old Mother Earth would consider short-lived features of her land surfaces. A few examples of these general principles may be here presented.

Divers Methods of Lake Production

Warped-Valley Lakes

A slight bending or breaking of the earth's crust will affect the slope of river basins and their valleys. If a valley slope is thus increased, its river will run faster and erode its valley deeper; but if a valley slope is decreased even to the point of reversing its direction, a lake may be formed in the depressed part of the valley. A peculiar lake in equatorial Africa illustrates this method of lake-production to perfection. The headwater area of a region drained by the Kafu and Katonga rivers has been slightly down-warped, so that their valleys now slope eastward instead of westward as formerly. The branching Kafu headwaters have thus been transformed, Fig. 1, into the branching Lake Kyoga, 150 miles in length. The Katonga headwaters are more completely submerged in the broad Lake Victoria, of similar measure in diameter. Parts of both rivers now flow backwards into their lakes.

Lake Victoria is the chief source of the Nile, which flows northward from it into Kyoga Lake by one of its branches and out by another. The little eroded Ripon Falls, next north of Lake Victoria, and the extremely narrow gorge below Murchison Falls, northwest of Lake Kyoga, testify to the recency of the time when the lakes were formed and the present course of the Nile was assumed.

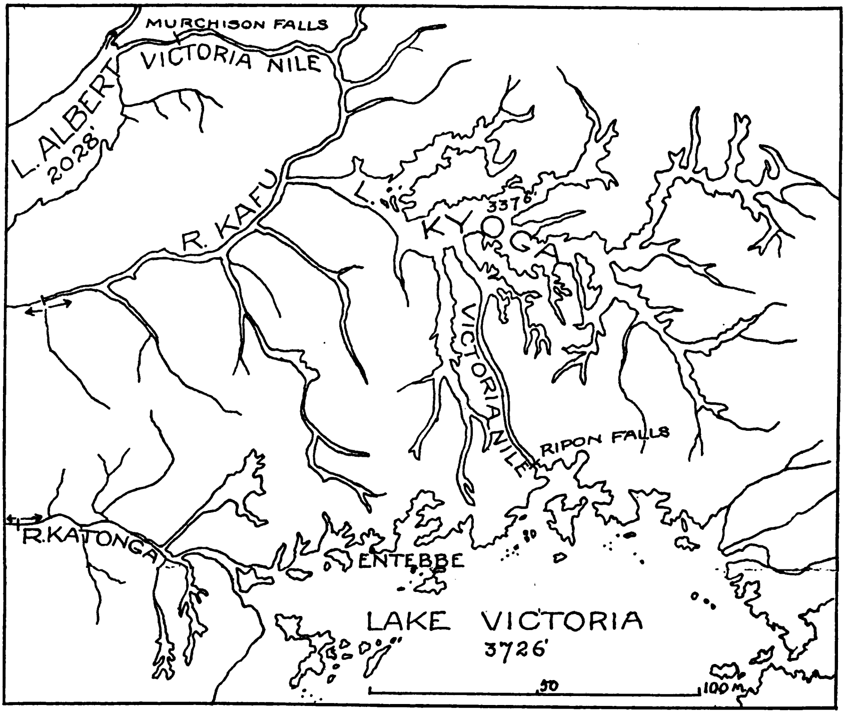

FIG. 1. Lakes Kyoga and Victoria, central Africa; reduced from map in report of E. J. Wayland, director, Uganda Geological Survey.

Fault-Basin Lakes

Certain lakes occupy depressions in the land surface which result from the breaking and tilting of huge blocks of previously nearly level earth-crust, as in Fig. 2. The deep fractures on which such blocks are displaced are known to geologists as faults, and the displaced blocks are called fault-blocks. When some of the blocks are raised to mountainous heights, as in the background of Fig. 2, the depression between them may be called an intermont trough or basin. Some such basins are of so recent a geological date of formation that they have not as yet been much filled by detritus washed down from the adjoining highlands, and rather deep lakes may then occupy a considerable part of their cavities. Central Africa again affords a typical example of this kind in the long and deep Lake Tanganyika; and the exceptionally long and deep Lake Baikal of north-central Asia may be of similar origin.

Other fault basins of more ancient origin are now largely filled with evenly spread layers of inwashed detritus, coarser and steeper-sloping near the base of the enclosing highlands, finer and more nearly level near the basin center. The basins are thus converted into flat, intermont plains, while the uplifted blocks are carved into rugged mountainous forms. Such basins are said to be aggraded, while the mountain blocks are dissected or degraded. Shallow lakes may then occupy the least filled parts of the plains, as in the foreground of Fig. 2.

It must not be imagined that the faulting or flexing of such crustal blocks took place suddenly or that the resulting troughs or basins immediately became filled with great bodies of water. The displacements were probably accomplished by many small movements separated by quiet pauses of years or centuries; and it is to be supposed that a considerable quantity of detritus was washed into the cavities from the enclosing highlands while the displacements were in slow progress. The displacements may have been, in some cases, so slow that the larger rivers of the deformed region held their courses, by cutting deep gorges through the uplifted blocks and filling the depressed areas with detritus. In all cases any lakes that were thus formed occupy merely such parts of the basins as are not otherwise filled. All such lakes may therefore be roughly classified with respect to the proportion that their water volume and area bear to the volume and area of the basin of deformation.

Intermont lakes will overflow if the climate is humid, but not if the climate is arid; for in the latter case evaporation from the lake surface disposes of all the water that the lake receives from rainfall and from inflowing streams and springs. Lakes without outlets are commonly saline, because as told above the minute amount of dissolved saline minerals brought in by their streams accumulates in them. If these lakes lie on the plains of smoothly aggraded intermont depressions, they may be so shallow even during the wetter part of the year that they evaporate in the drier part, leaving a smooth plain of silt in their place. Plains of this kind are called playas and the thin water sheets that temporarily cover them are known as playa lakes.

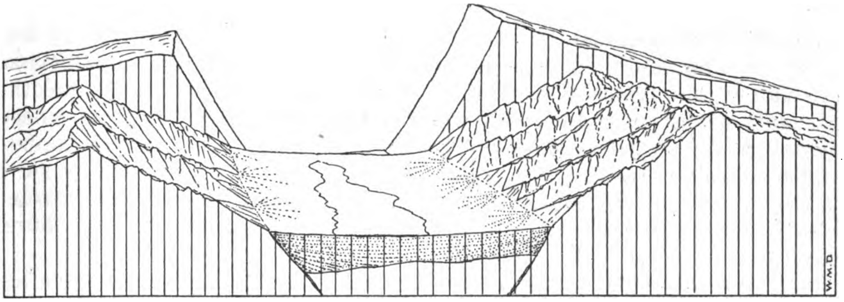

FIG. 2. Background: a depressed fault block between two upheaved fault blocks; foreground, the same, after a considerable period of erosion and deposition.

Nevada, Arizona and southern California, of arid climate, possess a good number of intermont depressions of earlier or later origin, the depth of which has been more or less diminished by deposits of inwashed detritus. Hence, besides some good-sized and rather deep lakes in the younger and less filled depressions of western Nevada, the flat, aggraded floors of many other depressions of the two states contain only dry lake beds or playas, mostly of moderate or small area. These are flooded, if at all, only after winter rains or summer downpours, and even then only by very shallow water sheets. But many of these heavily aggraded basins held much larger perennial lakes during the cooler and moister Glacial Period of modern geological times.

Landslide lakes

It sometimes happens that a steep-sided, stream-eroded canyon is blocked by a landslide, upstream from which a lake then rises, as in Fig. 3. A famous example of this kind occurred in a deep and steep-sided valley of the Ganges headwaters in the Himalaya Mountains of India in September, 1893. The slide descended some 4000 feet, leaving a great bare scar at its source, and forming a barrier in the valley two miles long and from 800 to 900 feet high. A lake gradually rose behind it and gained a length of over three miles. Then overflowing some eight months later, the outrushing flood rapidly cut a gash a mile long and nearly 400 feet deep through the barrier. The lake fell 25 feet in the first hour after its overflow began and 300 feet in the second hour. The resulting flood rose 160 feet 20 miles down the valley and from 50 to 60 feet 70 miles down. Yet such were the precautions taken and so well was the coming of the flood announced by telegraph to the villages down the valley that, although all houses and bridges were swept away, live stock was driven up the valley sides to safety and only one human life was lost, that of a religious devotee who insisted on living at the base of the slide. He was never found after the overflow took place.[1]

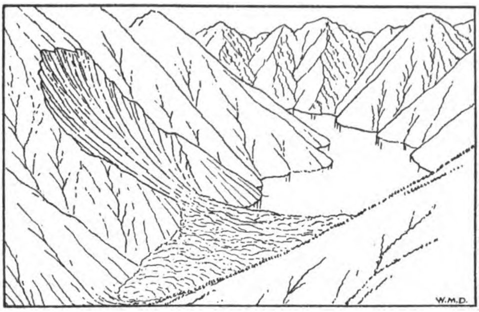

FIG. 3. Diagram of a landslide lake in a mountain valley.

If the obstruction produced by a landslide does not block a valley to a great depth, the outlet of the resulting lake will, on overflowing, cut down its course gradually and the lake will be slowly lowered. A great, prehistoric landslide, descending a slanting course of several miles on the Washington side, blocked the Columbia River about midway in its gorge through the Cascade Mountains and pushed the river toward the Oregon side; there the great river now has a cascading course among giant boulders and is striving to reestablish an even current and drain away its lake-like expansion that still remains next upstream from the obstruction; but as it has not yet succeeded in doing so, the slide must be of recent geological date. The name of the mountains through which the river has cut its deep gorge has been taken from the cascades of the river among the huge boulders of the slide.

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[1] Holland, T. H., The Landslip at Gohna, Garwhal. Rec. Geol. Survey, India, vol. 27, pp. 55-64, 1894.
Strachey, The Landslip at Gohna. Geog. Jour., vol. 4, pp. 162–170, 1894.
Lubbock, F., The Gohna Lake. Geog. Jour., vol. 4, p. 457, 1894.

Glacial Lakes

The great glaciers, which were formed on certain mountain ranges during the geologically recent, cooler and moister Glacial Period above referred to, scoured the bed rock of the highland valleys along which they crept, slowly and heavily, from higher to lower ground, and where the scouring was uneven, rock basins were excavated. Since the glaciers disappeared in the warmer and drier climate of the present, the basins that they excavated are occupied by lakes. Many Californian lakes are of this kind.

The modification of mountain forms produced by glacial erosion and the intimate association of lake basins with that extraordinary process may be made clearer by reference to Fig. 4. On the extreme left is shown the Preglacial form of a mountain range as produced by the prolonged action of ordinary weathering and streaming on an uplifted highland; not that all mountains had such forms in Preglacial time but that many of them had. The timber line was then at a high level, appropriate to the mild Preglacial climate. The dome-like summits give forth rounded, branching ridges and spurs, which separated correspondingly branching valleys; and down the continuously descending floors of the valleys, slender and nimble water streams ran in winding channels on the narrow valley floors.

In the left center, where the timber-line is lower by reason of a colder climate, a glacial system, consisting of several short branches heading in broad reservoirs and uniting in a long trunk, has taken possession of the upper part of a valley system and has reshaped the valleys to the satisfaction of the heavy and sluggish ice-streams. Each branch glacier has a concave surface in its gathering reservoir, but the trunk glacier assumes a convex surface as it sluggishly creeps down its course. Large as it is, all of its slow-moving volume is drained away by the slender ice-water stream that issues from a terminal ice cave. The several head glaciers have excavated great quarry-like cavities, known as cirques, in the valley heads, thus reducing the rounded mounts and ridges that enclose them to sharpened peaks and serrated crests; but unconsumed remnants of Preglacial dome-tops survive here and there. Each branch glacier preserves its individuality in the trunk; for ice streams do not mix their currents as water streams do. Hence the detritus dragged along from the narrowed spurs between the head reservoirs is seen in long "medial moraines" on the surface of the trunk glacier. That great glacier has transformed a narrow-floored, Preglacial valley into a strongly deepened and broadly opened but still steep-sided trough. The large size of the trough or ice-channel below the higher valley-side slopes is appropriate to the sluggish movement of the glacier, just as the small size of a valley-bottom stream channel is appropriate to the nimble flow of the water-stream.

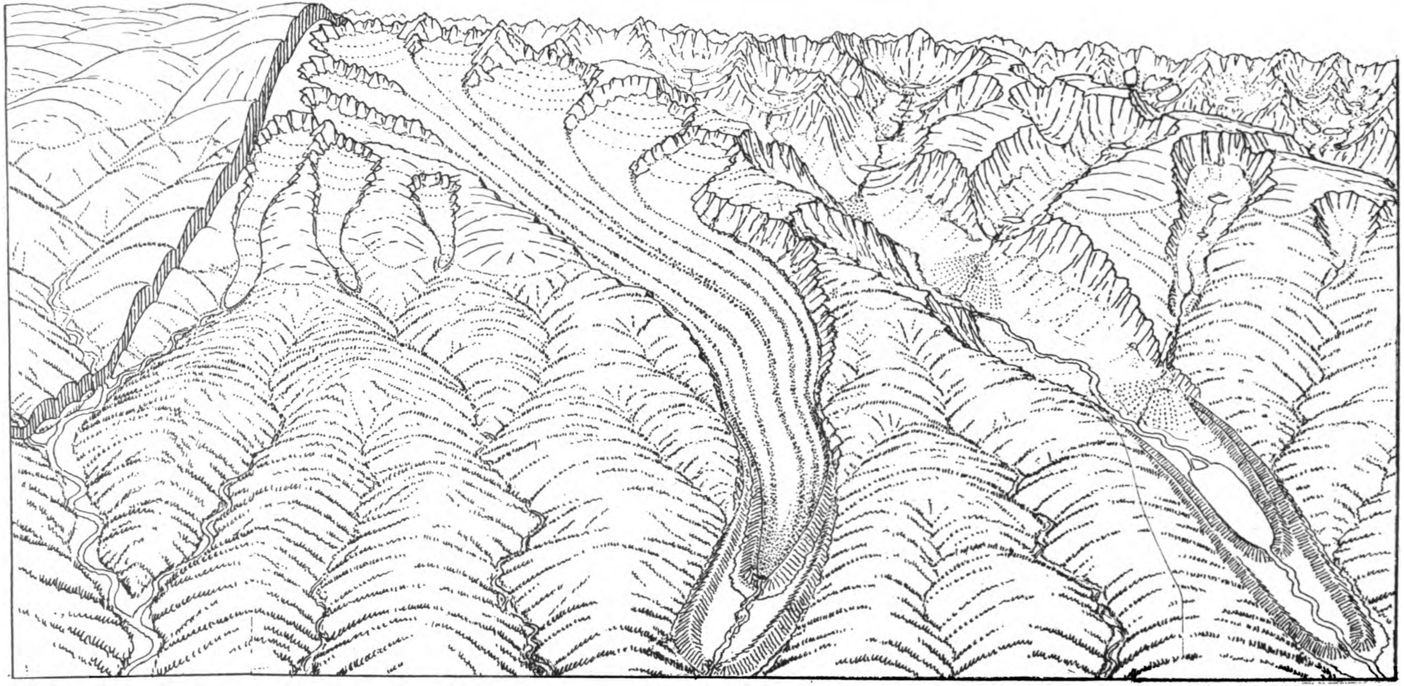

Fig. 4. Three-stage diagram, illustrating the glacial sculpture of mountains. On the extreme left, a non-glaciated mountain mass, with rounded spurs and narrow valleys, the work of ordinary erosional processes, chiefly weathering and streaming. Across the middle, same kind of mountains after they have been well modified by the glaciers which still occupy their valleys. On the right, the same, after the glaciers have disappeared, so that the cirques and troughs which they have excavated are exposed to view. Many small lakes are there seen, although no lakes existed in the mountains on the extreme left.

A small share of the detritus removed by the plucking and scouring action of the heavy, slow-creeping ice from the walls and floors of the cirques and troughs, as well as of that washed down upon the ice from the higher, ice-free surfaces, is deposited in a terminal moraine which loops around the end of the glacier in ridge-like form; but most of the removed detritus is carried away by the ice-water stream. The occurrence of a larger exterior terminal moraine indicates the presence at an earlier time of a larger glacier by which part of the cirque and trough excavation must have been done.

While these changes are going on, the parts of the range not occupied by glaciers are worn down lower by ordinary weathering and streaming without significantly changing their shape, to some such measure as is shown by the vertical face between the extreme left and the left center of the diagram.

The right half of the diagram exhibits the mountains as they appear after the glaciers have melted away in the milder climate of Postglacial time. The timber line is at a higher level again. The rock floors of the cirques are often scoured out in shallow basins, holding lakelets or tarns. Talus from the steep rock walls encroaches more or less upon the floors of the cirques and troughs. It is noticeable that the short side troughs which head in lateral cirques 'hang' above the much deeper floor of each great main trough. Streams, cascading down into the main trough, cut clefts and chasms in the lips of the hanging troughs, or hanging valleys as they may now be called, and build detrital fans below. The fans push the main trough stream toward the opposite side of the trough.

Small lakes may occupy shallow basins in the trough floor down stream from the cirques for a time after the disappearance of the glaciers; but many of them have been filled by stream-washed detritus which has built up or aggraded parts of the over-deepened floor in smooth flood plains or 'meadows.' The largest lake of the glacial system occupies the terminal part of the over-deepened floor, where the terminal moraine may aid in holding back its waters. The head of such a lake is partly filled in by the delta extension of the trough-floor flood plain.

Inasmuch as no great amount of talus has yet accumulated in the cirques, as the clefts cut in the lips of the hanging side valleys have not yet gained great depth, and as the terminal lake has not yet been completely filled by its growing delta, it must be inferred that the time since the disappearance of the latest glacial system is short compared to the time during which the valleys were occupied by that system as shown in the left-center of the figure, and shorter still compared to the time during which the mountain valleys, shown at the left end of the figure, were carved by ordinary weathering and streaming to the form they had before their occupation by ice.

The importance of glaciation in the production of lakes may be judged by the number and the size of such lakes in various parts of the world. For example, Okanagon, Arrow, Slocan and Kootenay in British Columbia, 60, 95, 23, and 68 miles in length, and the 65-mile Lake Chelan in Washington, all in valleys of the Columbia River system, occupy basins of glacial excavation. The same is true of the piedmont lakes of the Alps, including Annecy, Geneva, Thun-Brienz, Lucerne, Zurich, Constance, Ammer, Würm, and Chiem on the north, and Maggiore, Lugano, Como, Iseo and Garda on the south. Some of these lakes are over 1000 feet deep. They are all surrounded by beautiful mountain scenery, but the European examples have the additional and very picturesque attraction of long-established human occupation, while the American examples are for the most part in mountain wildernesses, scantily inhabited.

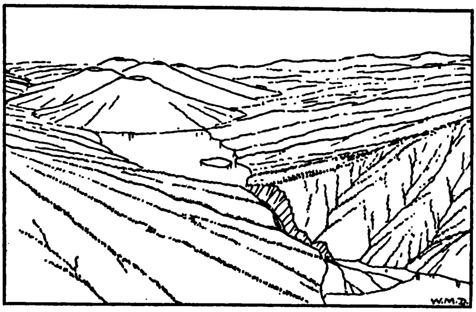

FIG. 5. A lake in a valley-head, above a group of volcanoes; the lake outlet has cut a notch in the divide at the head of the valley.

The great North American lakes, from those of the St. Lawrence system northwestward 2000 miles toward the Arctic Ocean, are all associated with the scouring action of the vast ice-sheets which covered northeastern North America in the Glacial Period, although it should not be asserted that they are wholly due to the excavation of their basins by ice action. Lake-basin production there may have been aided by warping of the earth's crust and by morainic obstruction of Preglacial river courses.

Volcanic Lakes

Volcanic cones or lava flows may obstruct valleys and produce lakes. Again an example may be taken from Africa: Lake Kivu, north of Tanganyika, is of this kind: its basin was apparently drained by a northward valley to the Nile before a group of great volcanoes barred the valley and turned its overflow southward via Tanganyika to the Congo, somewhat as in Fig. 5. The craters of extinct volcanoes may hold lakes. Among the most famous is Crater Lake in southern Oregon, 6 miles in diameter, 6240 feet in altitude and 2000 feet deep. It is surmounted by the 1000-foot cliffs of the enlarged crater or 'caldera,' which is believed to have resulted from the destruction of the upper part of the original cone, to which the name, Mt. Mazama, has been given. Three lakes lie in the craters of as many volcanoes next north of Rome. A number of similar but larger lakes are found in the volcanic cones of Java.

River-made Lakes

A river flowing in a serpentine or meandering course on a smooth flood plain frequently changes its course, leaving a narrow, curved lake in its previous channel, as in the left middle-distance of Fig. 6. Many such ox-bow lakes, as they are often called, are found in the flood plain of the lower Mississippi. A trunk river, which is well supplied with detritus from its headwaters, will build up or aggrade a flood plain near its banks more than at a distance to one side of them; those lower parts may then be occupied by marshy sloughs, as in the right foreground and left background of Fig. 6. Such a river may, indeed, build up its flood plain so actively that its side streams which build up their plains less rapidly are converted into lake-like water-bodies near their junction with the trunk river, as in the right background of Fig. 6. The branches of the Red River of Louisiana and of the lower Danube in Russia afford examples of this kind. Basins are sometimes enclosed or divided by the fan deltas of entering streams.

Artificial Reservoirs

Reservoirs, formed by building dams across valleys, closely resemble natural lakes. California possesses many such water-bodies.

Lake-like Bays and Lagoons

Arms of the sea, more or less completely land-locked, are also somewhat lake-like. It should be understood that Figs. 2 to 8, 13 to 15, 21, 25, 26, and 29, are not pictures of actual lakes and landscapes, but only ideal diagrams, drawn in a highly conventionalized manner with the object of supplementing the explanations of the text.

Lakes Are Ephemeral

It follows from the above principles that lakes should be regarded as representing only a passing phase in the action of the antagonistic processes that are concerned in the shaping of the land surface. The land-shaping processes are as a rule so slow in their action that we speak, properly enough from the viewpoint of human history, of the 'everlasting hills,' and we take little or no account of the changes suffered by most land forms—such as Mt. Sinai or the Seven Hills of

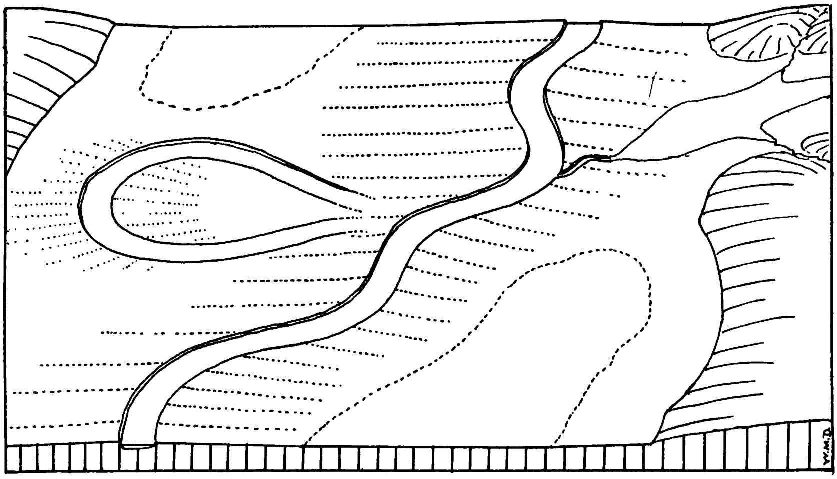

FIG. 6. Diagram of river-made lakes and sloughs.

Rome—during the latter part of the human period of geological time. But the student of geology must free himself of the idea that land forms are permanent, however fitting such an idea may be in the study of human history; he must strive to look on land forms as old Mother Earth herself would look upon them; that is, as forms which are, in terms of earth history, undergoing relatively rapid change.

Every element of the landscape should therefore be studied as representing a mere transitory stage of the systematic changes by which land forms pass from their earlier to their later, from their initial to their ultimate form. In such study those water forms which we call lakes are, because of the delicacy with which water assumes a level surface, very helpful in showing where hollows or basins in the land surface occur, and the changes in the outline and area of lakes are therefore reflections of the associated changes in the form of their basins. Thus conceived, the study of lakes gains much interest to an observant traveler; and thus equipped with a general understanding of the lakes of the world, the observer is better prepared for an appreciative understanding of the lakes of his own State.

Part II. THE LAKES OF CALIFORNIA

Sources of Information

California possesses a large number of lakes and lake-like water bodies of the various kinds above explained. The account of them presented below is believed to be more complete than any other that has yet been prepared. It has been made up in part from personal observation,[2] but much more largely from the study of articles by other observers and also from the examination of large-scale topographic maps. Although much information has been thus secured, the knowledge of California lakes is as yet by no means complete. It is therefore hoped that what is here told about those which have already been examined may lead to new investigations. Many of the less known lakes are unquestionably fertile subjects for further study, such as has already been given to the Alkali Lakes of Surprise Valley by R. J. Russell, to Medicine Lake of the Modoc lava beds by M. A. Peacock, to Sierran lakes of glacial origin by Eliot Blackwelder, to the glacial and volcanic lakes of Lassen Volcanic National Park by Howel Williams, and to other lakes by various investigators whose instructive essays are cited below. In case new studies of our lakes should include good photographs, preferably from an elevated point of view so as to show the whole breadth of the water surface in its setting with its near as well as its far shore, the State Division of Mines would be glad to add prints of such views to its growing collection of landscape portraiture.[3]

Although by no means all the lacustrine water bodies of the State are named on the following pages, it is believed that examples of all the different kinds of lakes that California possesses are included. Practically all the lakes named are shown on the large, two-sheet outline map of the State, published in 1929 by the U. S. Geological Survey on a scale of 1:500,000. For the sake of brevity the location of various lakes is concisely stated in relation to neighboring mountains, rivers or other large natural features, and occasionally in relation to near-by towns or cities. Surface dimensions are given roughly in miles as taken from the topographic maps of the U. S. Geological Survey, from the charts of the U. S. Coast and Geodetic Survey and from other sources; altitudes and depths are given, not always accurately, in feet.

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[2] The study of lakes has long engaged the author's attention; see his essay "On the Classification of Lake Basins," Proc. Boston Soc. Nat. Hist., vol. 21, pp. 315-381, 1882, and his shorter article on the same subject in Science, vol. 10, pp. 142-143, 1883.

[3] The address of the State Division of Mines is: Ferry Building, San Francisco, California.

Lakes in Young Fault-Block Basins

The Modoc lava field, which occupies a large area in the northeastern part of California with a thickness of 4000 or 5000 feet has, according to a recent study by Peacock,[4] been broken into several long fault blocks 10 or 20 miles in breadth, trending about north-south and crossing the northern border of the State into Oregon; the blocks have been gently and somewhat unevenly tilted so that their upraised edges form bold, little eroded scarps, from 200 to 400 feet or more in height. Three lakes occupy the down-tilted areas beneath the scarps, somewhat as in Fig. 7, and it would be difficult to find better examples of their kind. Clear Lake, one of three of that name in the State, lies 10 miles south of the Oregon line; it has been somewhat enlarged as a reservoir for irrigation and now measures 8 by 3 miles. Farther west is Tule Lake, formerly known as Rhett Lake, at an altitude of about 4140 feet. In 1884, it had an area of 184 square miles; in 1924, its area was halved; in 1930, it was "a small and shallow pond" which appeared to be vanishing. Still farther west is Lower Klamath Lake, 4175 feet in altitude and 27 by from 3 to 8 miles in size, of which only half lies in California. It also is diminishing in area, and much of it now is a reed marsh. The most probable cause for the diminution of Tule and perhaps of Lower Klamath Lake also is that their underground discharge is increasing. This, taken in connection with the steepness of their limiting fault scarps, suggests a very recent date for the faulting.

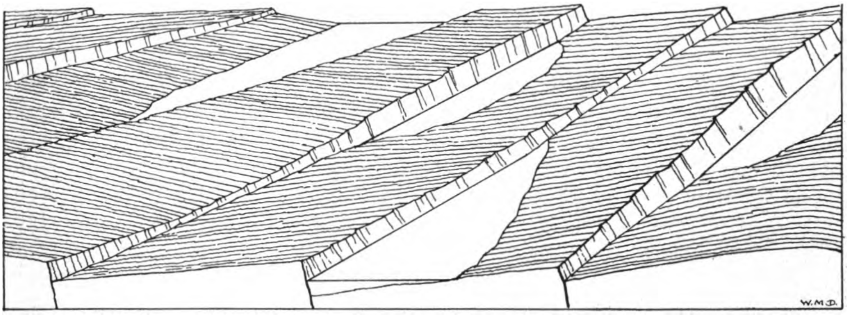

FIG. 7. Diagram of diversely tilted fault blocks, with lakes occupying the depressions.

A small example of a water-filled fault-basin is seen in Marlette Lake, as described by Reid.[5] It is 2 miles long, at an altitude of 8000 feet, in the broad-topped Carson range, the uplifted mountain block next east of Lake Tahoe in Nevada. The basin is so little filled with detritus that its origin would seem to be geologically recent.

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[4] Peacock, M. A., The Modoc Lava Field, Northern California. Geog. Rev., vol. 21, pp. 259-275, 1931.

[5] Reid, J. A., The Geomorphogeny of the Sierra Nevada Northeast of Lake Tahoe. Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 6, pp. 89-161, 1911.

Lakes in Aggraded Fault-Block Basins

Many intermont troughs and basins produced by strong faulting or flexing are found among the uplifted fault-block mountains of the Great Basin between the Wasatch mountain range of Utah and the Sierra Nevada, and a number of them are included within the arid northeastern and southeastern corners of the Golden State. The adjoining mountains are as a rule well dissected by deep valleys and the troughs or basins are therefore heavily filled or aggraded with down-washed detrital deposits which form nearly level plains, commonly known as 'valleys,' as in the foreground of Fig. 8. Relatively shallow playa lakes, many of them without outlets because of the dryness of the climate, lie on the lowest part of the plains.

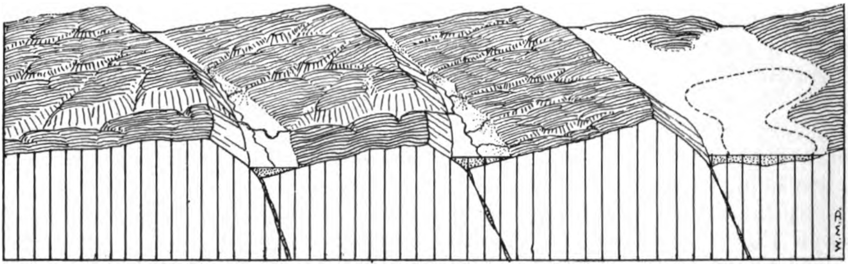

FIG. 8. Diagram of the great fault blocks of the northern Sierra Nevada, with the plain of Honey Lake on the east.

Playas are divided, according to Foshag, into two classes, water-tight or saline and leaky or dry. Water-tight playas are "salt encrusted areas, covered by a sticky tenacious mud when wet or a light fluffy soil when dry. During the rainy season they are often covered by shallow bodies of water and for the greater part of the year they are more or less moist. The water table seldom lies more than a few feet below the surface. The dry playas are entirely dry, only during periods of excessive or prolonged rainfall in the encircling ranges is water present on the surface for more than a few days at a time. Their surface consists of hard, smooth, sun-baked clay without visible concentration of salt."[6]

A typical example of the latter class is found in the shallow and variable Honey Lake, which lies on a broad and arid detrital plain of aggradation next below the great east-facing scarp of the northern Sierra Nevada, not far west of the Nevada line, somewhat as shown at the right end of Fig. 8. The scarp is believed to be the modified face of a great fault which constitutes one of the most distinctive features of the mountain range. It may therefore be believed that the Honey Lake area has been depressed and aggraded, while the strongly uplifted mountain mass was eroded. Recent slight movements on the fault are to be associated with several weak earthquakes felt there between 1880 and 1885, and in 1921.[7]

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[6] Foshag, W. F., Saline Lakes of the Mohave Desert Region. Econ. Geol., vol. 21, pp. 56-64, 1926.

This interesting lake is 3950 feet in altitude, 15 by 9 miles in area during wet winters, and yet then only from 1 to 4 feet in depth. Its water is alkaline and the lake is adjoined by barren alkaline flats. The surrounding plain is available for agriculture only where it can be irrigated. During dry summers the lake diminishes and occasionally vanishes, leaving an utterly barren playa with a surface nearly as smooth as that of the winter lake. The region then presents an extreme contrast to its condition when it was submerged to a depth of 350 feet, some thousands of years ago, by the northwest arm of a great inland sea of very irregular outline, to which the name of Lake Lahontan has been given. The shorelines made by its waves are still to be traced on the enclosing mountain slopes, but since then it has been evaporated away. One must therefore infer that the climate of the present epoch is warmer and drier than that of the epoch when Lake Lahontan was flooded. The climatic changes thus recorded probably occupied scores, perhaps hundreds of thousands of years; yet they are but a fraction of the time represented by the heavy aggradation of the Honey Lake intermont plain with detritus supplied by the downwearing of the adjoining mountains.

In the extreme northeastern corner of the State is the flat floor of a down-faulted and heavily aggraded trough, of the kind shown in the foreground of Fig. 8, known as Surprise Valley, Fig 9, over 40 miles long and 8 miles wide, with an altitude of about 4700 feet. It lies between the great uptilted, and immaturely dissected lava-bed fault blocks known as the Warner Range on the west and as the Hayes Canyon Range of northwestern Nevada on the east. On this flat floor

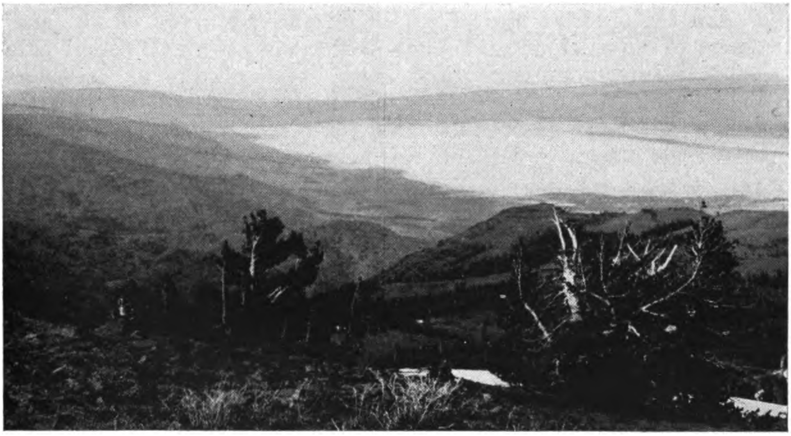

Photo by R. J. Russell.

FIG. 9. Looking northeast from crest of the Warner Range over Surprise Valley.

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[7] Kemnitzer, W., The Eagle Lake Earthquake of July 21, 1921. Seism. Soc. Amer. Bull., vol. 11, pp. 192–193, 1921.

lie three shallow and variable sheets of water which are named on the U. S. Topographic Map of their district as Upper, Middle, and Lower Alkali Lakes; but according to R. J. Russell, who has given an excellent description of them,[8] they are hardly known as lakes to the people who live on the surrounding plain. Two lakes may be seen from the crest of the Warner Range, looking northeast, Fig. 9, and southeast over the plain of Surprise Valley. Like Honey Lake, these shallow water sheets attain their greatest depth of a foot or two after winter rains; they almost or quite disappear in the summer, thus laying bare their silt beds or playas of the dry class. In winter when their water sheets are frozen over and in summer when their beds are dry and hard-baked, they may be driven over.

These lakes are bordered along their eastern or leeward shoreline by rather broad belts of salt flats, from the brine of which salt is won for local use, and sand dunes. Along their western side is a broad belt of grasslands, subject to temporary flooding from the mountains in the wet season. Here, marked by groups of willows, numerous springs bring forth the ground water that is fed by rainfall on the Warner Range. Some of the springs are hot; others bring fine silt to the surface and build small mounds around their vents, locally known as 'mud volcanoes.' The grassland belt is the best farming area of the intermont plain; as seen from the mountains its fields have a checkerboard appearance, in pleasing contrast to the uncultivated and almost valueless adjoining surface.

Like other lakes of their kind in the Great Basin these Alkali Lakes, the vague shorelines of which migrate with the winds, are the successors of an ancient and much larger lake, which flooded a large part of the intermont basin plain and to which the name, Surprise Lake, has been given. Its shorelines on the mountain slopes show it to have had a length of 70 miles and a depth of 550 feet. The climate then must have been cooler and rainier than now.

Goose Lake, as described by R. J. Russell[9], is another shallow water sheet, which occupies, at an altitude of 4800 feet, a large part of a moderately down-faulted trough below the western slope of the above-named Warner Range. It measures 30 by 10 miles, but one-third of its length extends into Oregon. A shallow gorge eroded through the lava beds on the south indicates that the lake formerly had a somewhat persistent discharge to Pit River, which flows westward through the highlands between Mt. Shasta and Lassen Peak to the Sacramento; but at present the lake overflows only when the water is brushed southward by a strong north wind, as happened in 1910.

Farther south, close to the eastern base of the Sierra Nevada lies Mono Lake, 6420 feet in altitude and 12 miles in diameter. This lake have been described by I. C. Russell[10]. It is believed to occupy a basin of depression, produced by down-faulting with relation to the up-faulting of the adjoining mountain range, but the enclosure of its waters may be due, at least in part, to volcanic barriers. As in the case of the Nevada lakes above described, a much larger lake, known by its high-standing shore lines, formerly occupied the basin in which Mono Lake now stands. The beauty of the present lake is much enhanced by the grandeur of the mountain scenery on its western side. The famous Tioga Road makes its descent there from the Sierra crest in a deep ravine. A considerable area south and southeast of the lake is covered with volcanic cones and lava flows, which have presumably diminished the extent that the lake might otherwise have. A volcanic island in the lake and several glacial moraines near it on the west will be referred to below in the sections on lakes of volcanic and of glacial origin.

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[8] Russell, R. J., The Land Forms of Surprise Valley, Northwestern Great Basin. Univ. Calif. Publ., Geogr, vol. 2, pp. 323–358, 1927.

[9] Russell. R. J., Basin Range Structure and Stratigraphy of the Warner Range, northeastern California. Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 17, pp. 388–496, 1928.

[10] Russell, I. C., Quaternary History of Mono Valley, California. U. S. Geol. Survey Eighth Ann. Rept., pp. 281–394, pls. 17, 19, 21, 1889.

Still farther south where the climate is even warmer and drier, a number of dry lake-beds on the lowest part of many intermont plains may be here instanced as showing that lakes were formerly more abundant than now, and as thus indicating the cooler and moister climate of that earlier time. South of Mono Lake 110 miles in Owens Valley and again at the eastern base of the Sierra Nevada, is the shallow Owens Lake, 3569 feet in altitude, 15 by 9 miles, formerly larger, now mostly reduced to a saline incrustation: this is therefore a playa of the saline class. To the southeast is the dry plain or playa of China Lake, 2124 feet in altitude, 7 by 2 miles; still farther east between the Argus and Slate ranges, is Searles Lake, 11 by 6 miles, 1623 feet in altitude, now heavily crusted over with a sheet of salt but containing a body of brine below, in consequence of which it has become the seat of an important chemical industry: this is another example of a saline playa. Again farther east, on the desert floor of the intermont depression known as Panamint Valley between the Slate and Panamint ranges, is Dry Lake playa, a white plain of saline clay, measuring 17 by 2 or 3 miles at an altitude of 1050 feet; another playa lies farther north in the same valley. Beyond Panamint Valley is the more famous Death Valley, of similar nature and again containing a playa of saline clays, but lying for the most part below sea level.

All of these now extinct lakes were, in the Glacial Period, on the course of the then enlarged Owens River, and each one of them except the last named then expanded to much greater area and depth than its saline successor of today and rose to the level of the lowest sag in the barrier to the east: thus each lake, as Gale, cited below, was the first to point out, overflowed to the next lower member of the series. At the level of each sag of overflow a shore line was more or less clearly marked around the lake by wave-built beaches, still discontinuously traceable. The lake of Death Valley, believed to have been fed by the overflow from Panamint Lake across Wingate Pass, does not appear to have risen to a sag of overflow as it was the farthest member of the series; hence its level, being dependent on inflow and evaporation, fluctuated up and down. Its faint shore lines have been detected at a number of points and indicate that it had a length of two or three score miles when at its highest level.

In the southern part of the Inyo Range, next east of the southern Sierra Nevada, are two down-faulted and aggraded 'holes,' known as Saline and Deep Spring Valleys. In each of them a saline lake or incrustation lies near the scarp of down-faulting. The first has been described by Gale[11] and by Knopf[12]; the second by Miller[13].

Many playas of the dry kind, representing vanished lakes mostly of moderate size, as in Fig. 10, might be mentioned as occurring in the arid southeastern part of the State. Like all their fellows these playas are covered with a very shallow sheet of water after heavy rains, and their clay floors are then impassable; but when the water is evaporated in the dry season the clay surface is firm and smooth, except where ridged and hard-baked ruts remain to mark the path of adventurous cars. One of the playas, known by the generic name of Dry Lake, 17 by 2 miles, is crossed by the Santa Fe railroad in its traverse of the northern part of the Mohave Desert. Another known as Bristol Lake, on the same railroad line farther east, is varied by the invasion of a black and ragged lava flow from a small volcanic cone on the west. Two smaller playas north of that railroad are crossed by the Cave Springs road to Death Valley. Others are too numerous to specify. It is on the level surface of a dry playa that the deceptive imitation of a lake, known as a 'mirage,' is developed on calm summer days. It is due to the super-heating of a thin layer of air next to the ground, so that when it is looked at from one side the light of the farther sky is reflected from it to the observer. As such reflection is a normal characteristic of true lakes, an inexperienced observer is likely so to misinterpret it in the desert.

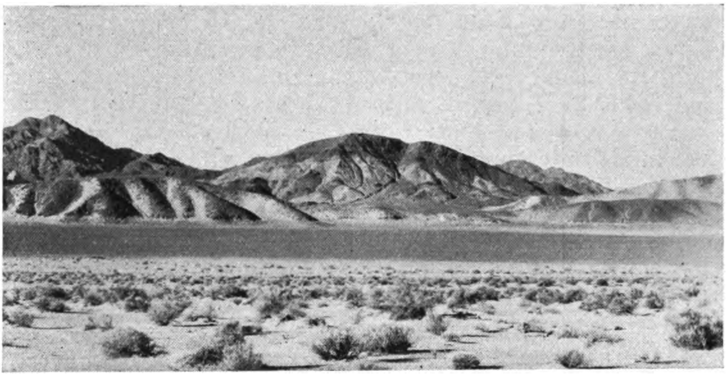

Photo by Eliot Blackwelder

FIG. 10. Silver Lake playa, in the southern part of a long depression which, farther north, is known as Death Valley.

Lake Elsinore, 5 by 1 or 2 miles, 1220 feet in altitude, is a shallow, brackish and variable water sheet lying in a faint depression at the highest part of the long, aggraded fault trough next northeast of the Santa Ana Mountains, 60 miles southeast of Los Angeles. Whether the shallow basin of the lake is determined by small and recent movements on faults, or by detrital fans washed in from the enclosing mountains has not yet been fully decided. The lake occasionally rises enough, in years of exceptionally heavy rainfall, to overflow northward by Temescal Creek along the fault trough to Santa Ana River. The scanty water supply of its district is made the most of in developing its scenic attractions.

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[11] Gale, H. S., Salt, Borax and Potash in Saline Valley, Inyo Co., Cal. U. S. Geol. Survey Bull. 540, 1914.

[12] Knopf, Adolph, A Geologic Reconnaissance of the Inyo Range. * * * U. S. Geol. Survey Prof. Paper 110, 1918.

[13] Miller, W. J., Geology of Deep Spring Valley, Calif. Jour. Geology, vol. 36, pp. 510–525, 1928.

Ancient Lakes of Intermont Basins

As the foregoing pages have presented accounts of playa lakes which vary with the seasons and of ancient lakes which indicate past variations of terrestrial climate through thousands of years, a brief mention of certain basin plains may be added which appear to indicate the occasional occurrence of still more ancient lakes. The part of the Sierra Nevada west of the above-described Honey Lake has been explained by Diller [14] as consisting of several west-sloping fault blocks with east-facing and more or less modified fault scarps, somewhat as represented in Fig. 8. Northeasternmost is Diamond Mountain block, some 40 miles in length, with a strong scarp, 2000 feet high overlooking the Honey Lake plain. The surface of the block slopes gently southwestward for some 20 miles into a long depression at the base of the next or Grizzly Mountain block; and that block, also sloping southwestward, is followed in its turn by the larger Claremont block which slopes down to the vast plain of the Great Valley. The inter-block depressions are aggraded with detrital plains, known as Indian and American valleys.[15] Lakes may have existed there intermittently during the time of slow faulting but none are present today. A larger example of an intermont basin which may have held a shallow lake at times during its aggradation is found in the so-called Sierra Valley, a broad plain which lies southeast of Indian and American valleys and which will be described below in connection with Lake Tahoe after the section on volcanic lakes.

Similar inferences as to the former occurrence of temporary lakes may be made with respect to several smaller intermont basin plains in the northern Coast Ranges, such as Potter and Long valleys, as well as to the somewhat larger basin-plain now mostly submerged beneath the waters of Clear Lake, 100 miles north of the Golden Gate, of which further account is given in the second-following section. All of these plains may have been intermittently flooded by shallow lakes during the slow down-flexing or down-faulting of their basin floors, but there is no sufficient reason for thinking that the basins were so suddenly produced that they at first held deep lakes which were then, after their rapid production ceased, slowly filled in with detritus and converted into plains as their outlets were cut down. Whatever lakes occupied the basins are best interpreted as shallow and temporary features compared to the associated fault-block mountains and basin plains.

The same statement holds good for the many longer and larger intermont basin plains of the southern Coast Ranges, of which typical examples are found in the Panoche and the Quien Sabe valleys, the first measuring 10 by 4 miles at an altitude of 1300 feet, the second 8 by 1 or 2 miles at an altitude of 1600 feet; both are drained by small

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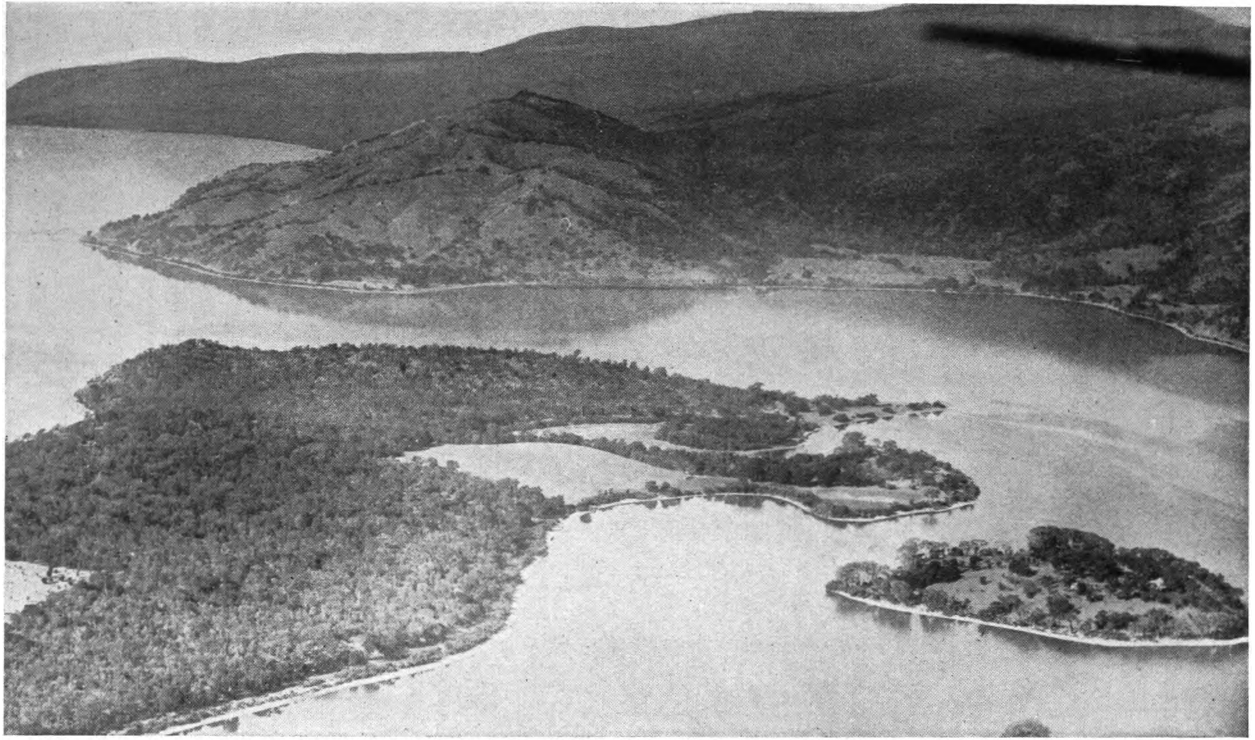
[14] Diller, J. S., Geology of the Taylorsville Region, California. U. S. Geol. Survey, Bull. 353, 1908.

[15] A view of the Indian Valley plain and of the dissected fault scarp to the west of it is given by Diller in Plate LI of his report on the Geology of the Lassen Peak District. U. S. Geol. Survey Eighth Ann. Rept., pt. 1, pp. 395–432, 1889.



Air-view by G. E. Russell, San Francisco

FIG. 11. The Narrows of Clear Lake, looking north.

streams through mountain gorges. Apparently on account of the southeastward decrease of rainfall, one of the larger southern examples, known as the Carrizo Plains, is peculiar in lacking a stream outlet. It is enclosed by a broad mountain mass on the west and on the east by the Temblor Range, the latter being one of the latest linear upheavals by which the breadth of the Coast Ranges has been increased at the expense of the Great-Valley plain. The smooth, treeless Carrizo surface, mostly given over to wheat fields, has been built up in faintly concave form by the inwash of detritus from the valleys eroded in the inclosing ranges; so that it now has a length of 40 miles, a width of 5 miles and an altutude of from 1950 feet at its middle to about 2600 at the ends. Over its lowest, medial part is spread Soda Lake, 5 miles long; a shallow water sheet after winter rains, a white and barren desert during the hot and dry summers. It lies near the western border of the plain because of the more abundant inwash of waste from the Temblor Range on the east.

Sag Ponds

Here and there along the Elsinore fault or rift and still more frequently along the more famous San Andreas rift, a slight movement on which caused the San Francisco earthquake of 1906, numerous little water-holding depressions, known as "sag ponds," mark the sites of local subsidences. One of the largest of its kind is Lake Elizabeth, about 2 miles long, on the San Andreas rift in the western part of the Mohave Desert, 50 miles northwest of Los Angeles. An unnamed sag pond, a mile in length, occurs on a rift at the base of the recently up-faulted El Paso Range, 6 miles northwest of Randsburg.

Landslide Lakes

The chief Californian lake of this class is Clear Lake,[16] which floods the greater part of an intermont basin plain in the northern Coast Ranges. It has given name to the county, in the center of which it lies. Long previous to the production of the lake the plain, measuring about 25 miles northwest-south, by 15 miles in greatest width, was drained by two outflowing streams, the divide between which may have been marked by low mountain spurs near the lake middle. One of the streams (Cold Creek) had cut a deep gorge westward through an enclosing range to Russian River, which led it to the Pacific 55 miles north of the Golden Gate; the other (Cache Creek) had cut a longer and deeper gorge eastward through the opposite range, which led it to the Sacramento and thus to the head of San Francisco Bay. After a time the eastern stream was crossed near its gorge entrance by a small lava flow, and its headwaters were thus diverted to the western stream.

At a still later date a landslide, descending only a few centuries ago from the southern side of the western gorge near its mid-length, filled it up for a mile or more to a higher level than that of the lava flow near the far end of the basin plain. The obstruction was so effec-

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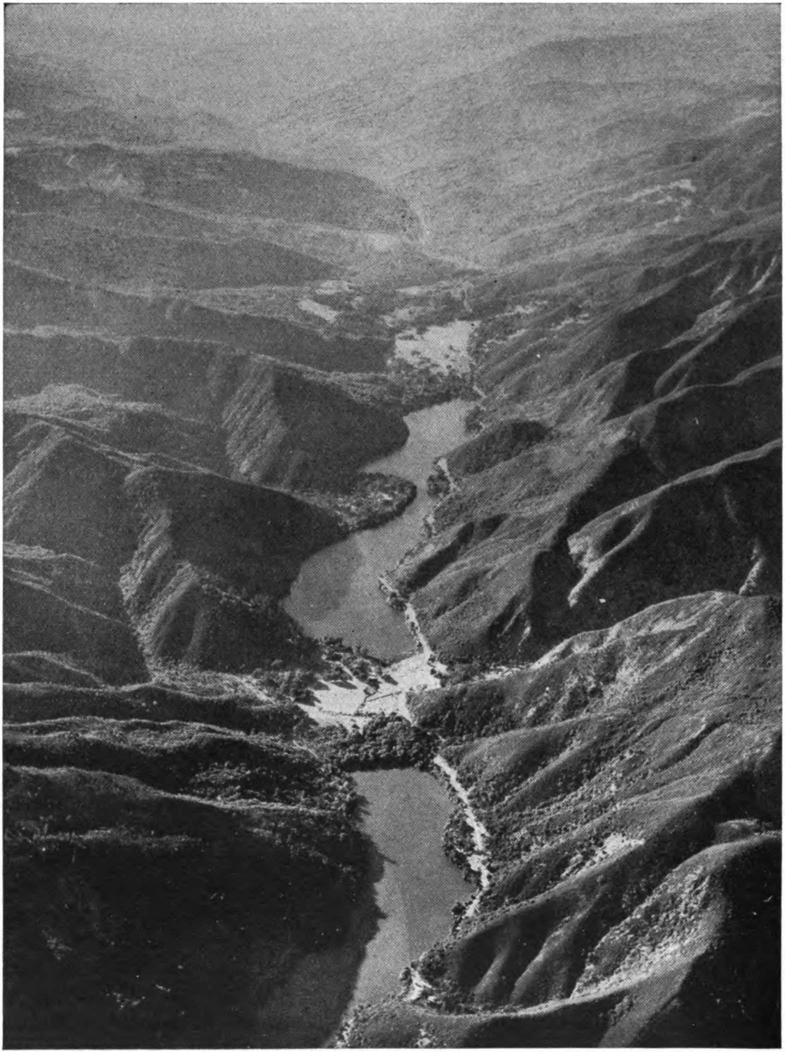
[16] This account is condensed from a study of Clear Lake by the author, as yet unpublished, in the preparation of which much assistance has been received from Olaf P. Jenkins, Chief Geologist, Division of Mines. It was he who first found the trench through the lava flow, which has proved to be of so great significance in the history of the lake.



Air-view by Erickson.

FIG. 12. The Blue Lakes, in the former outlet gorge of the Clear Lake basin plain. The obstructing landslide is just beyond a white field in middle distance. The two lakes are separated by the inwashed deltas of side streams nearer the foreground.

tive that a lake, fed by the streams that flowed into the basin, slowly rose higher and higher behind the slide, spreading over more and more of the plain, until it overflowed across a sag in the lava flow. The overflowing stream thereupon cut a trench (Redbank Gorge) across the flow, thus lowering the lake about 60 feet below its highest level, giving it a discharge through the eastern gorge, and re-enforcing the previously beheaded eastern stream (Cache Creek). The reduced lake now stands at an altitude of 1310 feet, with a size of 19 by 8 miles and a maximum depth of about 50 feet. Two narrow eastern arms are separated from the main western body at a picturesque Narrows, Fig. 11, near the lake mid-length. Had there been no outlet for the lake through the eastern gorge, the lake would probably have risen till it overflowed across the landslide in the western gorge and its outlet stream would very likely have washed away most of the slide in a destructive flood centuries ago, thus draining the lake and laying bare again the intermont basin plain. But such western overflow was effectively prevented by the presence of the eastern gorge. The landslide is of so enormous a volume that its removal by surface rills or leakage of ground-water is out of the question.

Since the formation of the lake its slender arm that at first occupied the part of the western gorge back of the landslide has been cut off from the main body of the lake by the broad delta of Middle Creek, which comes from the north; and the arm has been further shortened by the delta of Scott Creek, which entered it from the south. Its short remainder is now divided by the combined deltas of two wet-weather side streams, thus forming the picturesque little Blue Lakes, Fig. 12, beautifully enclosed by the steep sides of the gorge. These lakelets, therefore, belong in the class of lakes, the basins of which are barred by deltas, as will be told in a later section.

Clear Lake was artificially modified 20 years ago by the building of a 30-foot dam at the entrance to the eastern gorge and by the blasting out of a rocky barrier to a few feet greater depth near the entrance of the eastern outlet stream into the trench through the lava barrier, with the object of storing greater volume of water supplied by the winter rains and of withdrawing it to lower than ordinary lake level for irrigation of rice fields in the Yolo basin of the Sacramento in the summer. In consequence of these changes, the lake surface now usually stands a few feet below the level of the shore beaches that were formed before the changes were made. Unfortunately, the moderate rainfall of the region, 25 or 30 inches a year, does not supply the inflowing streams with much more water than is lost by evaporation, 53 inches in a year, from the lake surface, and therefore the outflow available for irrigation is usually small.[17]

The various changes that have taken place in the drainage of the basin have had a curious effect on the distribution of river fish. In consequence of the lava flow by which the head of the eastern stream was cut off and diverted to the western stream, one must infer that various species of fish belonging to the Sacramento system were transferred to the Russian River. This inference finds support in a study by Snyder who, nearly a quarter-century before the existence and the effects of the lava flow were discovered, pointed out that the fish of Russian River are like those "of the upper courses of the streams tributary to the Sacramento which flow from the western side of the Great Valley, the channel forms common to the main river [Sacramento] being absent" from the Russian River; and he therefore concluded that "the fish fauna of the Russian River was probably derived from the Sacramento," for "the Sacramento, a vastly larger and probably older system, not only contains all the [12 indigenous] fluviatile species known from the Russian River, but also others not there represented."[18] If the history of Clear Lake involved only its blockade by the landslide in the western gorge and the resulting shift of west-flowing stream through the eastern gorge to the Sacramento system, the above prophetic statement would have lacked confirmation; but the discovery of the lava flow and its effects confirms the prophecy by giving it a sound geological foundation.

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[17] Chandler, A. E., Water Storage on Cache Creek, California. U. S. Geol. Survey Water-Supply Paper 45. 1901.

A fine highway, ascending the lower part of the western gorge from Russian River valley, surmounts the landslide, skirts the Blue Lakes, crosses the delta plain of Middle Creek, follows the north shore of the main body of the lake, passes the Narrows and continues along the northern and shorter one of the two eastern arms. A side road, zigzagging up the mountain slope north of the main body affords a fine view of the lake and of the Konocti group of volcanoes, which reach altitudes over 3500 feet, adjoining the longer or southeastern lake arm. A considerable area of the basin plain, known as Big Valley, adjoining the main body of the lake on the south, is largely devoted to fruit raising.

This fine lake, the only lake in the northern Coast Ranges, is perhaps even more largely resorted to by summer visitors than Lake Tahoe in the Sierra Nevada. Its attractive scenery is therefore of a considerable esthetic value to the State, while its fisheries are of growing economic value. Moreover, in consequence of its production Lake County has become the home of many waterfowl which would otherwise not remain there.

Several other smaller lakes of landslide origin occur in the deeply eroded valleys of the Warner Range, already referred to as forming the western boundary of Surprise Valley in the extreme northeastern corner of the State. They have been well described by Russell,[19] who explains that their formation is favored by the occurrence of weaker volcanic beds under a capping of resistant basalt, so that the basalt, forming a 'rim rock' at the top of the valley sides, is sapped by the more yielding beds below it. One of these small lakes which, like the above described much larger fault-basin lake some 40 miles farther west, repeats the name of the still larger landslide lake in the northern Coast Ranges, measures only $\frac{1}{2}$ by $\frac{1}{8}$ miles, with a depth of 90 feet; it stands at an altitude of 5750 feet in a canyon 1000 feet deep in the western slope of the range. Two landslides, one from each side of the canyon, form its barrier; their scars are fresh-looking and the delta of the inflowing stream is small; hence the age of the lake is perhaps not over a century. Blue Lake, 10 miles farther south, is of similar and recent origin, but it is barred by a single slide. These two lakes drain to Pit River. Lost Lake lies in a sharply eroded canyon on the eastern slope of the same range at an altitude of 7400 feet; it is about 1700 feet in diameter; its delta is 50 per cent larger than its own area, and the scar of its landslide, a mile in length, is less fresh than those of Clear and Blue lakes. The outlets of these lakes all cascade down over the great boulders of their barriers.

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[18] Snyder, J. O., The Fauna of Russian River, California, and Its Relation to that of the Sacramento. Science, vol. 27, pp. 269–271, 1908.

[19] Russell, R. J., Landslide Lakes of the Northwestern Great Basin. Univ. Calif. Publ., Geog., vol 2, pp. 231–254, 1927.

Jess Valley is again, according to Russell, the filled-in and drained bed of a much older and larger landslide lake in the valley of Pit River, between Clear and Blue lakes, where that river, passing from the western base of the Warner Range, cuts a gorge through another up-faulted block of lava beds of less altitude. The nearly level surface of the valley measures 6 by 2½ miles at an altitude of 5300 feet. Its obstructing slide filled the gorge for half a mile and is estimated to contain 45,000,000 cubic yards of detritus. Several other meadows of similar origin are found farther down the gorge; but they are now trenched by the river, so that their remnants form terraces on the gorge walls. The same experienced observer reports that Eagle Lake, 30 miles northwest of Honey Lake, 5115 feet in altitude and 12 by from 2 to 4 miles in size, appears to be barred on its southeastern side by a landslide; if so, it would rank next after Clear Lake. He adds that this lake rises and falls without regard to rainfall, and that when it sinks numerous springs flow actively from the outer slope of its apparent barrier and supply streams that reach Honey Lake. This suggests that the barrier is of porous nature, as a landslide might well be, and that the water passages through it are intermittently closed and opened.

The small Kern Lakes, in the southern part of the remarkably rectilinear, north-south canyon of Kern River, west of Mt. Whitney in the southern Sierra Nevada, have been described by Lawson.[20] The southern one was originally barred by a rock slide which came down from the eastern wall of the canyon about 100 years ago and obstructed the canyon floor for a mile of its length; but the lake, now less than a mile across, has been much diminished by in-washed detritus. Kern River, continuing through the lake, has barred off its course by the high edge of its flood plain. The northern lake, a mile farther upstream, diminished by Kern River delta to a half-mile diameter, is separated from the lower lake by the detrital fans of two small streams from the east: it is believed that these fans were much increased in size in 1868, and that the separation of the upper from the lower lake dates from that year. Mirror Lake in the Yosemite Valley is also of rock-fall origin and will be described in the latter part of the next section.

A small lake, now extinct, was formed by a landslide in Grapevine Canyon, where the Ridge Road leading from Los Angeles northward to the central part of the State enters the southern part of the Great-Valley plain. This canyon is cut in the mountains which there curve around from the Sierra Nevada on the east to the Coast Ranges on the west; and the slide came from the mountain flanks on the west side of the canyon mouth. The uneven surface of the down-creeping mass is distinctly unlike the smooth and undisturbed slopes on either side of it. The lake which rose back of the slide has long since been filled with detritus, through which as well as through the slide itself a gorge has now been eroded. The thousands of travelers who daily follow the Ridge Road cross over the lower part of the slide, where the impetus of its flow banked it up against the east side of the canyon mouth; the road there makes a winding descent to the gently sloping "fan" of flood-washed stony and bouldery detritus that slants far forward on the vast plain. Another ancient slide seems to have blocked the stream farther up the same canyon near Old Fort Tejon.

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[20] Lawson, A. C., The Geomorphogeny of the Upper Kern Basin. Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 3, pp. 291–376, 1904. See pp. 343–345.

Two small landslide lakes are known in the northern corner of Lassen Volcanic National Park. One, Manzanita, originated according to Williams, cited below, about 200 years ago when a slide known as the Chaos Jumbles descended from Chaos Crags and blocked the valley of Manzanita Creek;[21] another, Reflection, lies in a hollow of the extremely rough landslide surface.

Small lakes or ponds of another kind lie at the head of valley-side landslides where a hollow is formed because the downward movement of sliding mass is commonly faster and farther at its under than at its upper surface, so that its head is tilted backward, as near the left foreground of Fig. 13. The irregularity of the down-sliding is often shown by diversely tilted overthrown trees. Large slides sometimes involve a great, slab-like mass that stretches half a mile or more along a mountain side and nearly or quite as far down the mountain slope, as in the background of Fig. 13. In consequence of its somewhat irregular descent, the smooth forms of ordinary degradation are changed to curiously disorderly forms. At the head of these greater slides, many small, pond-holding hollows may be formed. Such ponds are short lived, but they may linger longer than the larger ponds that are held back on valley floors by the bulging front of slides, because such ponds are soon drained away by the valley stream.

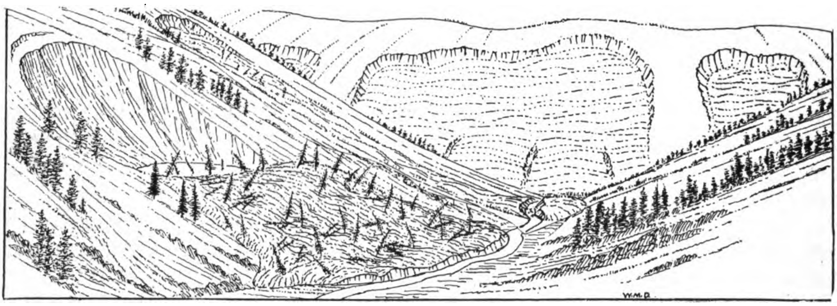

FIG. 13. Landslide diagram. In foreground, a recent slide with tilted trees; a small lake is held in the hollow back of it. A longer narrow slide is a short way beyond the nearer one. Three mountain-side slides are incompletely shown in the distance.

Landslides of this kind are numerous in those parts of the Coast Ranges where serpentine rock prevails, for that rock is prone to slip down from a mountain side after a valley is deeply eroded beneath it. Valley sides subject to sliding should evidently be avoided as far as possible by roads, pipe-lines, towers for electric power wires, and other structures for which stable foundations are desirable. The disorderly surface of slides may still be recognized years after any little ponds at their head have disappeared. However, a number of ponds still remain above the slides that abound on the slopes of Mustang Ridge, northeast of Peachtree Valley, which is in its turn northeast of the much larger Salinas Valley in the southern Coast Ranges.

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[21] A fine view of the lake is given in the frontispiece of Day and Allen's report on Lassen Peak, cited below.

According to a personal communication from Dr. J. H. Maxson of the California Institute of Technology, several landslide ponds occur in the serpentine areas of the Klamath Mountains in the northern part of the State.

Lakes of Glacial Origin

Glaciation of Californian Mountains

Most of the larger lakes named in the preceding sections lie on relatively low ground, presumably because they are associated with down-faulted areas or with down-sliding valley sides. The numerous lakes of the kind now to be described are found on mountainous highlands where their basins have been produced by the erosive action of great glaciers which covered considerable spaces in the higher parts of the Sierra Nevada and smaller spaces of other Californian mountains. That remarkable episode occurred in the Glacial period of recent geological time, a period of cooler and snowier climate on mountains that is believed to have been contemporaneous with the cooler and moister period when lakes were formed on interior desert lowlands.

In order to appreciate the importance of glaciation in respect to lake production, it should be understood that, in Preglacial time, there were in all probability no lakes on the Sierran highlands. The reason for this is that the highlands had then been long subjected to the ordinary erosional processes of weathering and streaming, which would have destroyed any lakes that might have been produced there in earlier times by faulting as described on foregoing pages, or by ancient volcanic action as will be described on following pages. Lake Tahoe is hardly an exception to this rule, for although produced by a combination of faulting and volcanic action, as will be told below, it is not on the highlands but occupies a deep trough below them.

The great Sierran glaciers of that time, the area of which has been mapped by Blackwelder,[22] had their sources in lofty valley heads where heavy snows were collected below the mountain summits and transformed into ice. The many separate glaciers that had their source in the high valley heads of each of the Sierran river systems united in broad sheets as they slowly advanced down the highlands of the western Sierran slope, but the sheets were irregularly interrupted by spurs and mounts that rose from the highlands to a greater height than the ice thickness. Then the sheets narrowed into faster moving ice tongues as they were drained down the previously eroded trunk valleys. While the descent was in progress the glaciers were melting to smaller and smaller volume as they reached lower and lower levels of warmer climate. By reason of the more extended area of their gathering grounds and of the larger number of their converging branches, the glaciers of the long western slope had greater size and pushed their ends down to lower levels than those on the shorter and steeper eastern slope of the mountains, which are diagrammed in Fig. 4. Thus the Tuolumne glacier, west of Mono Lake, extended for 34 miles along the crest of the range and ended 35 miles southwest of the crest; while for the San Joaquin glacier, south of that lake, the corresponding dimensions are 52 and 25 miles. On the steeper eastern slope, the measures along the crest and down the slope from it were much smaller.

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[22] Blackwelder, Eliot, Glacial and Associated Stream Deposits of the Sierra Nevada. Cal. State Div. Mines, Mining in California, July–October, 1932, pp. 303–310.

Two Epochs of Glaciation

Two terminal moraines are shown in each glaciated valley of Fig. 4. The lake that may have once occupied the earlier formed, outer basin has been filled by inwashed detritus and converted into a plain or meadow. The inner basin still holds a lake. Such is very commonly the case in the glacial troughs of the Sierra Nevada. It is inferred from this and from other evidence of a similar nature that there have been at least two epochs of glaciation. Critical studies of this kind in various parts of the world have indeed shown that the Glacial period was composite in the sense of including several alternations of colder Glacial epochs and milder Interglacial epochs. An excellent discussion of this problem for the Sierra Nevada is given by Blackwelder in his essay cited below; he there shows that, besides two later Glacial epochs, which he calls the Tahoe and the Tioga epochs, the work of which is illustrated in Fig. 4, there were two earlier Glacial epochs, the records of which are much modified and obscured by later erosion. The lakes produced in the latest or Tioga epoch are the chief subject of the following pages; but first the relation of the recent Tioga glaciers to the less recent Tahoe glaciers may be briefly stated.

There are four chief points to be considered. First, the Tahoe glaciers of the Sierra Nevada were longer than the Tioga glaciers and extended farther down their valleys, somewhat as shown by the moraines in the right half of Fig. 4. Thus while the largest Tioga glaciers ended at levels of about 6000 feet on the western and about 7000 feet on the steeper eastern slope of the mountains, the Tahoe glaciers ended perhaps 1000 feet lower. For example, in the Tahoe epoch the branch glaciers of Tenaya and Merced canyons joined to form the great trunk Yosemite glacier, which continued about 7 miles and ended at about the level of 4000 feet near the end of the great cliff-walled trough, the shape of which was largely produced by the intense glacial erosion of a pre-existing narrower and shallower valley, as Matthes has so well shown.[23] But in the Tioga epoch, the branch glaciers each ended in its own trough where lakes of the same names are now found, about 8 miles above the trough junction.

Second, the Tahoe moraines are many times larger than the Tioga moraines; some of the largest measure nearly 1300 feet in height. Third, by reason of their greater age, the cliffs of the Tahoe cirques are weathered to somewhat subdued forms, the cirque-floor basins are occupied by meadows, and their trough-end lakes are in nearly all cases now converted into detrital plains. Fourth, whatever lake basins the Tahoe glaciers produced at higher levels than the Tioga moraines are not now to be distinguished from the basins now occupied by the lakes of the Tioga epoch.

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[23] Matthes, F. E., Geologic History of the Yosemite Valley. U. S. Geol. Survey Prof. Paper 160, 1930.

The following pages, therefore, refer chiefly to lakes produced in the Sierra Nevada by the later Tioga glaciers, even if their work consisted largely in cleaning out detritus-filled rock basins of earlier Tahoe production. Some brief statements concerning extinct lakes of the Tahoe stage will be given at the close of this section.

All the Californian lakes of glacial origin are of relatively small size, but many of them are of great beauty; and as they are often closely associated with the superb scenery of the High Sierra they are greatly enjoyed by lovers of outdoor life when the hot summers of the lowlands prompt ascent to the cooler mountains. As the glacial lakes of the State far outnumber all others, much has been written about them. By far the best illustrations of these lakes, many of which are accessible only to mountaineers, are to be found in the annual volumes of the Bulletin issued by the Sierra Club of San Francisco, in which they are pictured in an incomparable series of photographs.[24] The loftiest glacial lakes occupy basins in cirque floors; these will be first described. Next will come those somewhat irregular lakes which lie at intermediate altitudes on trough floors or on the open Sierran highlands. Lowest are those which fill the terminal overdeepening of the enlarged valley-troughs, where they are partly enclosed by terminal moraines; these are most frequently visited.

Lakes in Glacial Cirques

Cirque lakes occupy shallow rock-basins in the floors of the great cliff-walled cavities excavated at the heads of glacial troughs, somewhat in the form of enormous quarries, 500 or 1000 feet deep and half a mile or a mile across. They abound in the High Sierra, where they are found below the loftier summits at altitudes of from 8000 to 10,000 feet. There and more strikingly in the northern and southern part of the range, where the mountains are not so high, cirque lakes were developed best on northeastern slopes, where snow drifting was favored of the westerly winds and where snow melting by sunshine was least effective. The peaks above such lakes are therefore unsymmetrical, being more rounded on the southwest slope and deeply cliffed on the northeast.[25] The cirques of the earlier Tahoe epoch, not reoccupied by the Tioga glaciers, are now, as above noted, weathered to somewhat dulled forms; their floors are cluttered over with talus from their walls and their lakes are converted meadows. Those occupied by the later and smaller Tioga glaciers are as bare as if recently abandoned by the ice.

Where several cirques are excavated opposite each other in the radiating valleys of a massive, dome-like mountain of Preglacial sculpture, the cirque lakes are separated from one another by high spurs, the upper parts of which are narrowed into saw-tooth pattern, while the central summit is reduced to a sharpened peak, as in Fig. 14; but where several Preglacial valleys, heading in a group of mountains, converge and join in a trunk valley, the cirque-headed troughs have a sim-

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[24] Among many others the following views are especially fine: Sierra Club Bulletin, vol. VII, Pls. 31, 40; vol. VIII, Pl. 6; vol. IX, Pls. 16, 20; vol. X, Pl. 226.

[25] Gilbert, G. K., Systematic Asymmetry of Crest Lines in the High Sierra of California. Jour. Geology, vol. 12, pp. 579–588, 1904.

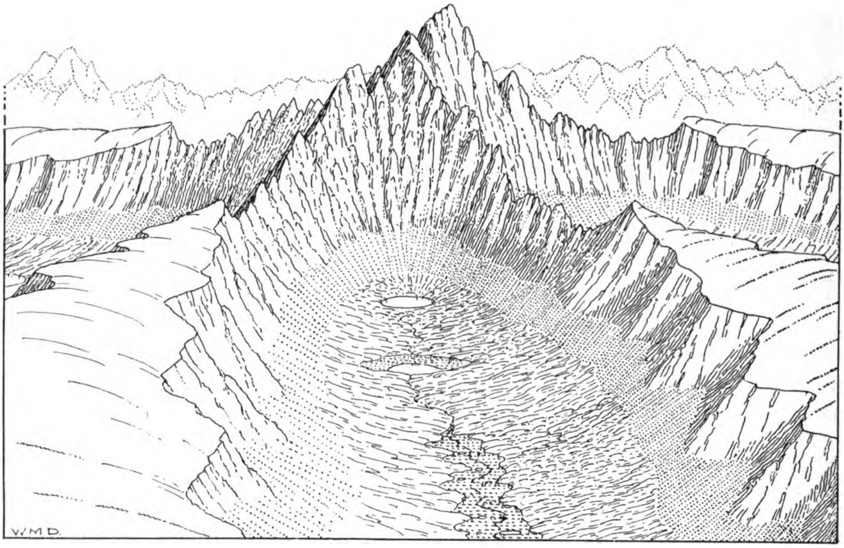

FIG. 14. A group of cirque-headed glacial troughs radiating from a lofty peak which has been sharpened by cirque recession on all sides. Small lakes or meadows are seen on the foreground trough floor.

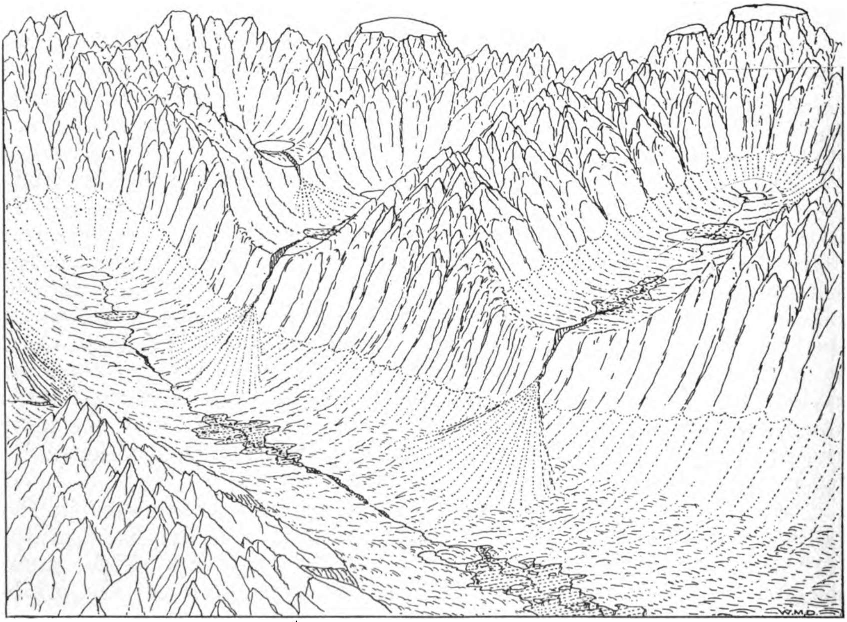

FIG. 15. A mountain group from which several converging, cirque-headed branch troughs all join the same trunk trough. The branch troughs "hang" over the trunk trough. Small lakes or meadows are seen on the trough floors.

ilar converging arrangement and the smaller ones 'hang' over the larger one, as in Fig. 15; here all the cirque lakes of such a group are rather closely associated. But it should be understood that vast as is the work of glacial sculpture in the High Sierra, the erosional work of ordinary weathering and streaming by which the mountains had been given their Preglacial form was vaster still.

It is in intimate association with these profoundly sculptured mountain forms that cirque lakes (Fig. 16) should be studied. If taken alone they cannot be appreciated, for their little basins are but a subordinate part of the great cirque-headed, cliff-walled troughs in which they are contained. The basins differ in no significant respect from the rest of the gigantic excavation, except that they are scoured to slightly greater depth so that they hold water. The same principle holds true, though perhaps less manifestly, in the study of all the other lakes of the State; it should be applied to the fault-basin and the landslide lakes already described and to the volcanic, river-made and other lakes to be detailed below. All are but items in the evolution of the landscape which they for a time adorn.

The Tehipite, Mt. Whitney and several other sheets of the U. S. Topographic Map show many striking examples of lakes in trough-head cirques excavated in the dome-like masses of the High Sierra. Regarding the concave cirque heads, W. D. Johnson, a skillful topographer, wrote in homely fashion: "These sharp outlines were suggestive of nothing so much as the scattered remnants of a sheet of dough on the biscuit board, after the biscuit tin has done its work." [26] A fuller discussion of these remarkable mountain forms is given by Lawson.[27]

Sometimes a series of small lakes, like beads spaced on a string, is seen occupying a succession of rock basins beginning in a cirque floor and continuing down stream from it. It is to be presumed that the convex rock sills between the basins were more resistant to glacial erosion than the basin rocks; the greater resistance may be due to the number and attitude of the joints in the rock quite as well as to variations in its composition.[28] Such series of lakes are to be seen at the headwaters of Iillilouette Creek, 16 miles southeast of the Yosemite Valley; also between Mammoth Mountain and Mammoth Crest, high up on the eastern slope of the Sierra, 22 miles south of Mono Lake; again, but more confusedly, farther south in the remarkable Sixty-lake Basin at the headwaters of Kings River under Mt. King, and still farther south under Mt. Genevra. Garnet Lake and Thousand-island lakes, about 9800 feet in altitude, are exceptional among cirque lakes in being beset with rocky islets; they are drained by a roundabout stream to the Middle Fork of San Joaquin River.

Cirque lakes become less abundant and disappear in the northern and far-southern Sierra Nevada where the altitude of the range decreases. Gold Lake, 2 miles long, on a head branch of the Middle Fork of Feather River, is one of the largest in the northern mountains.

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[26] Johnson, W. D., Grade Profiles in Alpine Crests. Jour. Geology, vol. 12, pp. 571–578, 1904; reprinted in Sierra Club Bulletin, vol. 5, pp. 271–278, 1905.

[27] Lawson, A. C., The Geomorphogeny of the Upper Kern Basin. Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 3, pp. 291–376, 1904; see pp. 357–362. This article gives in Pl. 42 an excellent view of a fine cirque lake next southwest of Mt. Whitney, the highest summit of the Sierra Nevada.

[28] A striking view of a rock sill is given in Pl. 4 of Johnson's article above referred to.

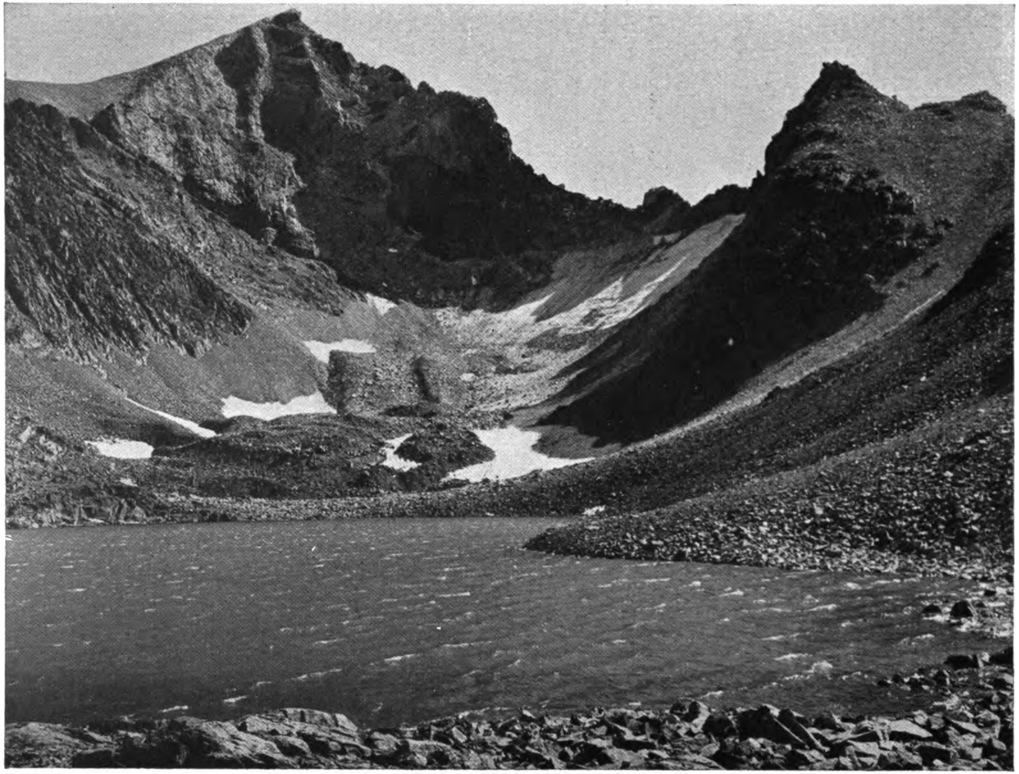

Photo by Ansel Easton Adams, Courtesy of Sierra Club.

FIG. 16. Typical glacial cirque and lake. Rodgers Peak from the north, Sierra Nevada.

Not so far north a group of cirque lakes is found under Sierra Buttes near the North Fork of Yuba River; one of them is figured by Turner.[29] Another northern group is found around Fall Creek Mountain, near the South Fork of the same river. Farther south, where the mountains gain altitude, cirque lakes are to be counted by the hundred, as may be seen on the Mt. Goddard sheet of the U. S. Topographic Map at the head of San Joaquin River, the Mt. Lyell sheet east of the Yosemite Valley, and the more southern Mt. Whitney sheet. In the far-southern part of the range, a number of small cirque lakes occur on the headwaters of Kaweah River in the Sequoia National Forest; fourteen such lakes, more or less converted into marshes, are clustered around the headwaters of the North Fork of Stanislaus River, as shown on the Big Trees topographic map.

Irregular Lakes on Trough Floors

Lakes of this kind lie on unevenly scoured trough floors, where some parts are a little deeper than others. They are of long-oval outline when they occur in narrow, steep-walled, well-smoothed troughs, but they are of very irregular outline and are often beset with low rocky islets and knobs of round-scoured rock when they occur in broadly open, flat-floored troughs. Their depth by no means indicates the depth of trough-floor excavation beneath the floor of a Preglacial valley, but only the excess of scouring of one part of the floor below another part. These irregular lake basins therefore correspond to the deeper parts of the bed of a stream channel eroded by running water. As their depth is usually small they are frequently replaced by inwashed stream detritus and thus converted into nearly level meadows, as in the foreground of Figs. 14 and 15.

Apparent examples are seen in the irregular Silver, Loon and Pleasant lakes, in branch troughs of the South Fork of American River. It may be here noted that, although glacially enlarged valley-troughs are commonly described as U-shaped in cross profile, they are, as a rule, much more like well opened, round-bottom Vs. It is only by way of exception, and in the Sierra Nevada only in the terminal troughs of Tahoe glaciation, that the U-shape is closely approached, as is shown by the rarity of cliff-walled valleys of the Yosemite type, among which Matthes has shown that Kings River, Hetch Hetchy and Tehipite troughs are to be included with the Yosemite masterpiece.[30]

Lakes on Ice-Scoured Sierran Highlands

The irregularly scattered lakes of the broad Sierran highlands lie in small and shallow rock basins. Where the country rock is granite, they are formed amid smoothly scoured and severely barren undulations of the surface; but on weaker rocks, where forests alternate with grassy glades, they are associated with a more pleasingly picturesque scenery. One should here, in order to appreciate the transformation of the landscape that ice-scouring has accomplished in the glaciated areas, recall what was said above as to the absence of highland lakes in Preglacial time, and to that may be added Lawson's description of

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[29] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Downieville folio (No. 37), Fig. 3, 1897.

[30] Matthes, F. E., *op. cit.*

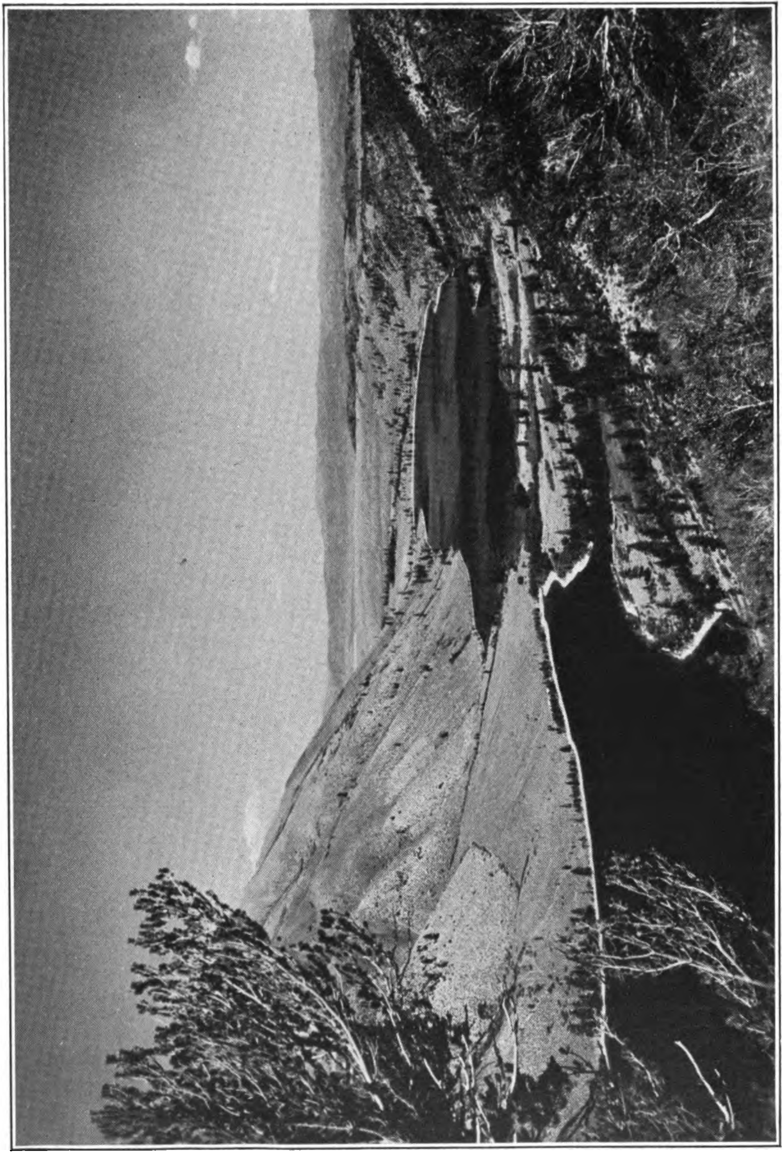

Photo by Eliot Blackwelder, Courtesy of Geological Society of America, Fig. 10, vol. 42, no. 4.

FIG. 17. Twin Lakes, Sierra Nevada.

a non-glaciated southern area of the mountains. That experienced observer wrote: "A remarkable feature of the upland surfaces is the prevailing absence of water courses or incisions of any kind due to stream cutting. * * * The surface is everywhere encumbered by blocks of granite, formed by the intersection of joints and dislodged by the heaving action of frost. The veneer of loose blocks is so thick that the waters from summer rains and from melting snows do not gather in runways and so establish lines of stream cutting, but flow in a diffused fashion between and beneath the blocks. * * * It is only when we get to the bottom of the canyons and cirques that the granite is tight enough to hold water on its surface. It would thus appear that these upland surfaces are as free from the attack of running water as are the driest deserts."[31]

It may be said further that the highland veneer of granite blocks has probably been continued from an early time before the upheaval of the mountain mass, when it was part of an extensive and soil-covered lowland of long-continued degradation, which in its southern area at least probably had a desert climate; for on such a lowland the well disintegrated soil at the surface must have been underlaid by less disintegrated joint blocks to a certain depth below the surface. Not that all the joint blocks on the non-glaciated highlands of today were then prepared, but that the present blocks there are the direct successors of their ancient predecessors. A veneer of similar blocks probably overspread all the highlands in Preglacial times, but in the areas that became glaciated they were swept away down to firm rock, as the following quotations show.

Lindgren has described the more barren highlands as "vast stretches of dazzling white granitic rock surface, worn and rounded"; and he adds concerning a climax area: "There are few more imposing sights than the ice-swept rock deserts of the * * * Devil's Basin,"[32] a wide area at an altitude of 8200 feet, dotted with little lakes or with grassy flats at the head of the South Fork of American River, 7 miles southwest of Lake Tahoe. Humphrey Basin is a similar area, over 11,000 feet in altitude, at the head of the South Fork of San Joaquin River; it is included on the Mt. Goddard map sheet, which shows the well-named Desolation Lake, a mile in length. The depth of these highland lakes is not a true measure of glacial erosion that the highlands have suffered; it measures only the excess of erosion in the lake basin below that on the neighboring surface.

Blackwelder remarks that the ancient glaciers left on the scoured highlands "vast areas of comparatively bare granite, upon which so little forest grows that the rocks stand out gray and white."[33] The monotony of these rock deserts is here and there relieved by tree-covered patches of glacial detritus; also by perched boulders, left there when the ice cover melted away. The undulating and polished granite surface, more or less scaled off, and the perched boulders are well illustrated in Matthes' report (Pls. 35B, 36, 37B), referred to above.

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[31] Lawson, A. C., *op. cit.*, pp. 313, 314.

[32] Lindgren, Waldemar, U. S. Geol. Survey Geol. Atlas, Pyramid Peak folio (No. 31), 1896.

[33] Blackwelder, Eliot, Pleistocene Glaciation in the Sierra Nevada. Geol. Soc. America Bull., vol. 42, pp. 865–922, 1931. This paper contains several excellent views: Fig. 1, a lateral glacial trough hanging high over a main trough; Fig. 2, talus in a glacial trough; Fig. 3, glacially polished granite with perched boulders; Fig. 10, a divided trough lake, here reproduced in Fig. 17; Fig. 15, a meadow replacing a glacial lake.

The lakes on the scoured highlands are not infrequently rimmed with low walls or 'ramparts' of boulders and stones, which have been, according to Gilbert,[34] gradually pushed out from the shallow bottom in the milder spells of winter weather, when the ice expands a little after having contracted during preceding spells of severe cold. When its temperature falls 7° Fahrenheit, the ice of a frozen lake a mile across will contract a foot. Cracks are then opened through the ice; but they are soon closed by new-formed ice. A warm spell then expands the ice and it spreads a little on the shores. A repetition of this through many winters has resulted in shoving outward all boulders that the shore ice rests upon, and thus in time a rampart is formed.

Trough-End Lakes

Lakes lying at the end of an over-deepened valley-trough of the Tioga epoch, where their retention is aided by a loop of morainic ridges, are nearly always of simple, long-oval outline and of a considerable depth, some being as deep as 200 or 300 feet; but their original length is somewhat decreased by the inwashed delta of the trough stream. Thus Merced Lake, in a trough-end basin of the Tioga epoch drained by Merced River to the Yosemite Valley, is now partly filled by a forested delta, well shown in Plate 12B of Matthes' report. Blackwelder notes that near these lakes, "acres of polished and grooved rock are a familiar sight"; also that the rock polish is here better preserved than on similar surfaces scoured by the earlier Tahoe glaciers.

The oftenest seen lake of this important class is Donner Lake, which lies next north of and well below the line of the Southern Pacific Railroad where it descends the eastern slope of the Sierra Nevada from Donner Pass to Truckee Valley. It is 3 miles long and is enclosed by heavy morainic ridges, in great part of Tahoe age, at an altitude of 6095 feet. Another terminal lake in the same drainage basin, but less often seen, as it lies higher in the mountains to the northwest, is Independence, about 2 miles long at an altitude of nearly 7000 feet. The southern or main upper course of Truckee River, which drains Lake Tahoe, leads to several well known terminal lakes: Fallen Leaf Lake is a popular summer resort on the southwest side of Lake Tahoe; it is of about the same length as Donner, but has an altitude of nearly 6400 feet. The Tioga terminal moraine, close around the foot of the lake, is of small size; the Tahoe moraines, enclosing the Tioga moraine, are vastly larger; one on the southeast of the lake is over 3 miles long and rises 900 feet like a great railroad embankment. The glacial origin of this beautiful lake was recognized by Le Conte 60 years ago; but in stating that the basin of Lake Tahoe also had been filled by ice he showed an exaggerated idea of the dimensions of the ancient glaciers.[35]

A recent and well illustrated essay by Jones on this picturesque district limits the glaciers to more moderate lengths.[36] Cascade Lake, 3 miles northwest of Fallen Leaf and of similar size and altitude, is pictured as seen from above in a compound loop of morainic ridges. A mile farther north is Emerald Bay, like the other two lakes except that it lies at the level of Tahoe, with which it is connected through a frontal opening in its 600-foot moraines. Echo Lake, a mile long, 3 miles south of Fallen Leaf, belongs in a somewhat different class, as it lies at an altitude of 7500 feet just back of the lip of its lateral trough, which hangs 500 feet above the floor of the main and much larger trough of the Upper Truckee glacier. This lake is peculiar in having its waters artificially diverted from Truckee River and led southward through a tunnel to a head branch of the South Fork of the west-flowing American River, to increase the volume of that Fork for electric power. Other examples of trough-end lakes are Emigrant, Huckleberry and Tilden, each about 2 miles long and all in steep-sided branch troughs of the North Branch of Tuolumne River.

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[34] Gilbert, G. K., Lake Ramparts. Sierra Club Bulletin, vol. 6, pp. 225–234, 1908.

[35] Le Conte, Joseph, On Some Ancient Glaciers of the Sierra. Am. Jour. Sci., 3d ser., vol. 10, pp. 126–139, 1875.

[36] Jones, Wellington, Glacial Land Forms in the Sierra Nevada South of Lake Tahoe. Univ. Calif. Publ., Geogr., vol. 3, pp. 135–157, 1929.

A peculiar group of glacial lakes, well illustrated on the topographic map of the Yosemite National Park, 1932, is found in the semicircular glacial trough which is drained by the well-named Reversed Creek back of Reversed Peak, about 12 miles south of Mono Lake. The creek heads in June Lake, which is apparently held by a terminal moraine at the northern end of the eastern arm of the semicircle; it then flows south through Gull Lake and, curving to the west, enters Silver Lake, from which it flows north along the western arm of the semicircle and thus, a few miles farther north, reaches Grant Lake, held by another terminal moraine, through a gap in which the outlet, there known as Rush Creek, continues to Mono Lake, about 7 miles distant.

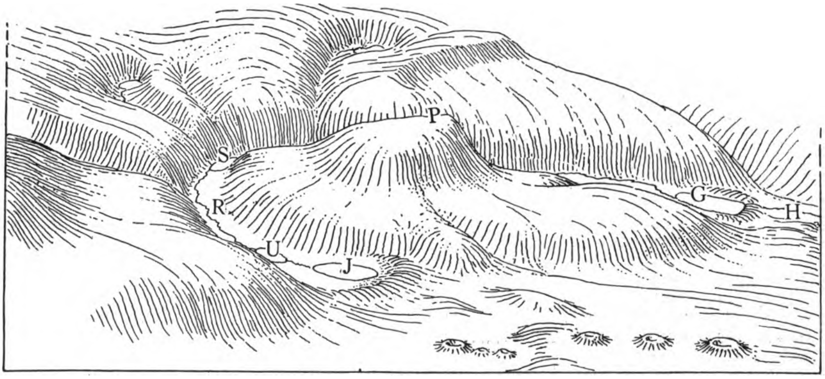

FIG. 18. Sketch of relief south of Mono Lake, looking southwest; June Lake (J); Gull Lake (U); Reversed Creek (R); Silver Lake (S); Reversed Peak (P); Grant Lake (G); and Rush Creek (H).

Twin Lakes, 3 miles in combined length, stand at altitudes of 7076 and 7096 feet on a fork of Walker River, 15 miles southwest of Mono Lake. They result from the subdivision of a single, trough-end lake by inwashed detrital fans near its mid-length, as explained and illustrated by Blackwelder, whose fine photograph of them is here reproduced in Fig. 17. These lakes are shown with many others on the Bridgeport topographic map. The most famous double lake of this kind is in Switzerland, where an originally single lake, occupying the long and greatly overdeepened valley trough of the River Aar, has been divided into Lakes Brienz and Thun by the combined deltas of two opposite side-streams; the beautiful town of Interlaken stands on the fans; and the outlet of Lake Brienz winds between the fans to Lake Thun.

A group of tarns, known as the Volcanic Lakes, occupy the floor of the large, cirque-like trough head of Dougherty Creek, a south branch of the Middle Fork of Kings River; they are believed to be not of volcanic but of glacial origin and are said to have taken their name from some volcanic rock near by.

Extinct Glacial Lakes in the Sierra Nevada

It has been noted above that the trough-floor and terminal lakes of the long Tahoe glacial troughs are now as a whole converted into treeless meadows or forested valley floors of inwashed detritus, the meadows being attractive features of the Sierran highlands. Such meadows and plains are longer than the lakes which they replace, because their gently slanting surface extends farther up the valley-trough floor than the level surface of the lake could reach.

The best known example of this kind occupies the great cliff-walled glacial trough of the Yosemite Valley, of which Matthes has given an admirable description, above cited. The lake which originally filled the gouged-out terminal rock basin of the trough and which was partly held back by the terminal moraine of its 20-mile Tahoe glacier, is estimated to have had a length of 5½ miles, and it was therefore one of the largest of its class. There is little question that the marvelous scenery of the Valley would be more marvelous still if the lake had not been destroyed. Another detrital plain occupies the lower part of Tenaya Canyon, the eastward extension of the Yosemite. Mirror Lake (see Matthes' Plate 47a), a small pool on that plain, is not a remnant of the rock-basin lake that the plain replaces, for that lake has been completely filled; the little lake is due, again according to Matthes, to the active, avalanche-like downfall of rock blocks from the oversteepened cliffs, by which the stream that formed the plain has recently been slightly obstructed. One of the longest aggraded troughs in the Sierras is found in the Tuolumne Meadows; it probably conceals several trough-floor rock-basins.

Non-Sierran Glacial Lakes

The only glacial lakes in the mountains of southern California are two small ones, Dollar and Dry, in cirques below Mt. San Gorgonio, the dominating dome-like summit, 11,485 feet in altitude, of the San Bernardino Mountains.[37] The mountains in the northern part of the State contain a considerable number of glacial lakes, all of small size. Curiously enough, Lassen Volcanic National Park, between the Sierra Nevada and Mount Shasta, contains according to Williams[38] many more glacial than volcanic lakes. The park district pretty surely possessed a good number of lava-barred lakes during a former time of greater volcanic activity; but the lakes then produced have been converted into plains and some of the lakes found there today appear to result from the excavation of these filled basins by ice action. To the south and east of Lassen Peak, Helen, Emerald, Shadow and Cliff lakes, each only a quarter-mile or less in diameter, occupy basins wholly the product of glacial erosion. Farther east Rainbow, Twin, Swan and the six Cluster lakes have been similarly produced. The same may be said of a score of little wet-weather ponds on the lava flow of Crater Butte, east of the park center. Horseshoe Lake, nearly a mile across, and Juniper Lake, about 1 by 2 miles, in the southeastern part of the park, occupy intervolcanic depressions modified by glacial action.

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[37] Fairbanks, H. W., and Carey, E. P., Glaciation in the San Bernardino Mountains, California. Science, vol. 31, pp. 32–33, 1910.

[38] Williams, Howel, Geology of the Lassen Volcanic National Park, California. Univ. Calif. Publ., Bull. Dept. Geol. Sci. vol. 21, pp. 191–385, 1932.

Farther northwest, a good number of small cirque lakes occur in the Klamath Mountains at altitudes of from 6500 to 7500 feet.[40] A small lake of this kind in the neighboring Siskiyou Mountains is shown in Fig. 19 and a small meadow-marsh resulting from the filling of such a lake is shown in Fig. 20.

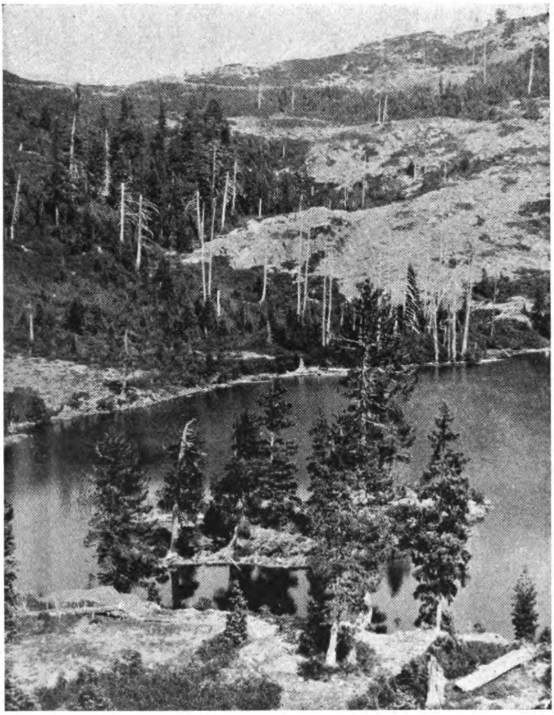

Photo by J. H. Maxson.

FIG. 19. Island Lake, Siskiyou Mountains.

Lakes in Basins of Limestone Solution

Limestone is a relatively soluble rock: some of its underground fractures or "joints" are commonly more or less enlarged into passages or caverns by the solution of their walls in ground-water. Such enlargement commonly begins along the intersection of two joints; and as it progresses surface streams frequently disappear by descending at "sinks" into the underground passages. If such an underground passage is obstructed, a pond or lake may be formed over the sink. It has been suggested by Baker[41] that Bear Lake, which had a length of about a mile in a flat-floored valley at an altitude of about 6700 feet in the San Bernardino Range, is of this origin. A dam at the lake outlet now holds back a reservoir 5 miles long when filled to capacity.

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[40] Hershey, O. H., Ancient Alpine Glaciers of the Sierra Costa Mountains in California. Jour. Geol. vol. 8, pp. 42–57, 1900. See the Sawyers Bar and Seiad sheets of the U. S. Topographic Map.

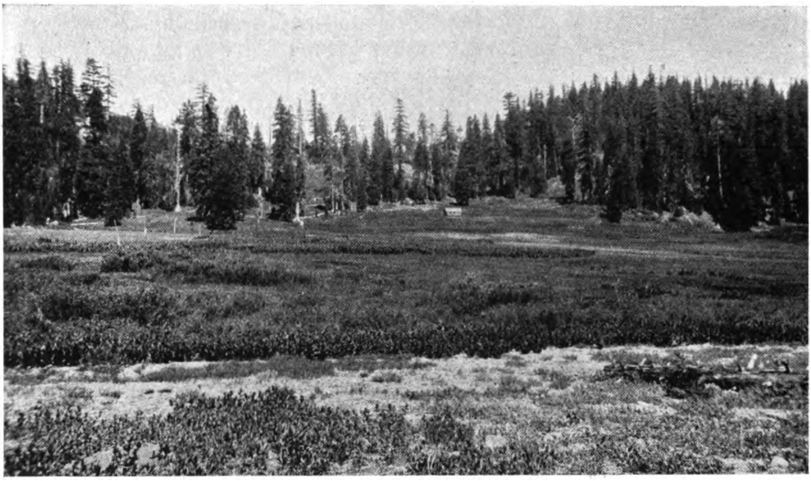

Photo by J. H. Maxson.

FIG. 20. A marshy meadow replacing a small glacial lake, Siskiyou Mountains.

In certain limestone districts lakes are formed by the obstruction of rivers where calcareous tufa is deposited in river channels, apparently where springs charged with limestones in solution emerge from the channel bed. No lakes of this kind have been reported in California.

Lakes of Volcanic Origin

Several lakes of volcanic origin occur in Lassen Volcanic National Park in the northern part of the State, but the lakes there are mostly of glacial origin, as already told. They are all well shown on the topographic map of the park (1929). Two of the best known are Butte (formerly Bidwell) and Snag lakes, each about a mile long and at an altitude of about 6500 feet: they were first described by Diller[42], but the following details are taken from a later and fuller account by Williams.[43] He explains that the valley of a north-flowing stream was obstructed by a lava flow in preglacial time, as in the upper right corner of Fig. 21, and a lake several miles in length was formed upstream from the obstruction. The basin was, however, much modified by a glacier which for a time crept along the valley floor, although it did not succeed in wholly removing the lava barrier. After the glacier disappeared a lake occupying the modified basin was more or less filled with marshy deposits. Then a small volcano, known as

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[41] Baker, C. L., Mohave Desert Region in southern California. Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 6, pp. 333–383, 1911. See p. 364, Pls. 41, A and B.

[42] Diller, J. S., A Late Volcanic Eruption in Northern California. U. S. Geol. Survey Bull. 79, 1891.

[43] Williams, Howel, *Op. cit.*

Cinder Cone, was built up on the western side of the valley and a ragged lava stream that was extruded from its base spread over a medial part of the original lake basin, as in the middle of Fig 21, thus producing Snag Lake.

The small Hat Lake, at the northeast base of Lassen Peak, is the youngest lake in the park, as it was formed in consequence of the obstruction of the headwaters of Hat Creek by a mudflow from the peak during the eruption of 1915.

Lakes not infrequently occur in the craters of recently extinct volcanoes. Thus a small lake occupies the summit cavity of Crater Butte, east of Lassen Peak. A little wet-weather lake of the same kind occupies the crater of an unnamed cone about 20 miles farther east; a tiny lake is mapped at an altitude of 12,000 feet in the crater of Shastina, a secondary volcano on the west slope of Shasta; and two minute lakes are found in the craters of small cones on Paoha Island in Mono Lake.[44]

Medicine Lake in northeastern California stands near the center of the Modoc lava field which has been mentioned above in the account of several fault-basin lakes at the northern boundary of the State; and this lake like those has been described by Peacock,[45] in brief as follows: A broad and low dome of lava was built up by local eruptions of fluid lavas on the larger field; and the dome was crowned by an imperfect ring of later cones, of which Mt. Hoffman is one, most of them made of cinders; their brown or reddish color is more or less concealed by a forest cover. The highest member of the ring, Big Glass Mountain, about 8000 feet in altitude, composed of dark obsidian or volcanic glass, which appears to have been viscous when erupted and which therefore accumulated in a huge pile instead of spreading out in nearly level flows. The ring includes also several smaller cones of pumice or frothy lava, white and barren. Some of these eruptions are of extremely recent date; one of the lava flows, when just at the limit of its advance, pushed and charred a tree trunk that is still standing at the lava edge.

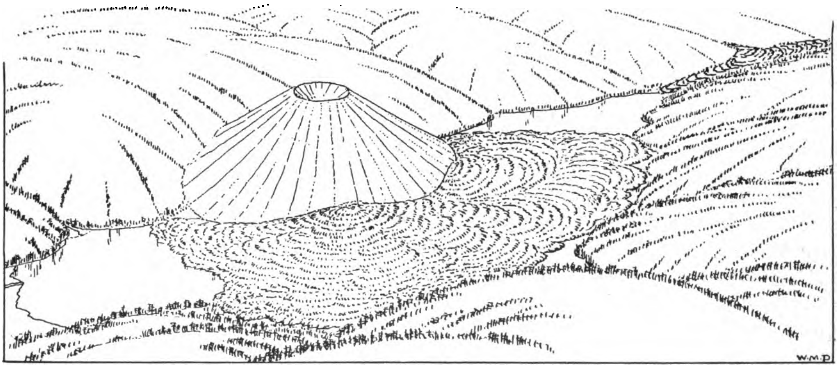

FIG. 21. Diagram of volcanic lakes.

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[44] Russell, I. C., Quaternary History of Mono Valley, California. U. S. Geol. Survey Eighth Ann. Rept., pt. 1, pp. 261–394, 1889. See pp. 373.

[45] Peacock, M. A., The Modoc Lava Field, Northern California. Geog. Rev., vol. 21, pp. 259–275, 1931

Within the ring of cones a hollow space remains less filled up, and in its lowest part lies Medicine Lake, about 2 miles long at an altitude of 6500 feet. It is clear and fresh although it has no overflowing outlet.

Similar to but much smaller than Medicine Lake is Thurston Lake, which occupies a deep hollow that is accidentally enclosed by the up-building of several volcanic mounts around it in the volcanic district which adjoins Clear Lake, above described, on the south. The water surface in these two lakes is said to stand at the same level and to vary equally with change of seasons, as if a connection between the lakes were maintained by underground percolation. Several similar hollows among these volcanic mounts are now occupied by detrital plains.

Ancient Volcanic Lakes

A number of lava-barred lakes of earlier origin in the Lassen Peak region have been converted into meadows. For example, about 20 miles southeast of the peak, an ancient lava flow ran into and formed a dam across the valley of the North Fork of Feather River, and the river thereupon rose in a lake; but what with inwash of detritus and erosion of an outlet gorge through the dam, the lake has disappeared. Its bed is known as Big Meadows, 15 miles in length,[46] now in part flooded in a reservoir as told below. Similar features are found around Mt. Shasta; the largest plain, known as Shasta Meadows and measuring 20 by 10 miles, lies 20 miles northwest of the great volcano at an altitude of 2750 feet. It is probable that several similar meadow plains would be found near Lassen Peak, were it not that their unconsolidated detritus has been removed by glacial scouring. Juniper and Horseshoe lakes, already described in the section on lakes of glacial origin as occupying inter-volcanic depressions modified by glacial erosion, deserve mention here also, because in preglacial time they were probably represented by detrital plains.

In his account of Mono Lake, I. C. Russell made brief mention of a former lava-barred lake, now represented by a small playa basin; it lies about 30 miles northeast of Mono. A well defined but extinct lake of the same origin in Truckee Valley is now, according to Lindgren,[47] represented by Martis Valley, a plain of fine sediments 4 miles across at an altitude of 5900 feet, next east of the town of Truckee. The lake rose to an altitude of 6000 feet in consequence of a lava barrier that blocked Truckee River not far to the east. The river has now not only washed a quantity of sediment into the basin but has drained away the lake by cutting down a gorge through the barrier; since then it has trenched a shallow valley along the northern border of the lake-basin plain.

A larger example of a plain that replaces a volcanic lake occupies Mohawk Valley in the northern Sierra Nevada. The original depression is believed to have been a down-faulted trough, drained westward by the Middle Fork of Feather River, and therefore resembling the two similar fault-troughs farther northeast, drained by the North fork, as above described under fault-basin lakes. According to Turner[48] the Mohawk trough was blocked on the northwest by a heavy body of lava; the lake thereupon rose to a level of 5100 feet, thus gaining a length of 11 miles and a width of 2 or 3, with a northeast arm 7 miles long. Although now drained by a gorge cut through the lava barrier, the lake-shore terraces, more or less dissected by local brooks and the bottom deposits at levels of from 4400 to 4600 feet memorialize the vanished lake. Not far south is the larger intermont basin plain of Sierra Valley of similar origin; it will be described in the next section with Lake Tahoe.

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[46] This ancient lake is mapped in Plate 47 of J. S. Driller's report on the Geology of the Lassen Peak District. U. S. Geol. Survey Eighth Ann. Rept., pt. 1, pp. 395–432, 1889.

[47] Lindgren, Waldemar, U. S. Geol. Survey Geol. Atlas, Truckee folio (No. 39), 1897.

Two small examples of extinct, lava-barred lakes are known near the above-described Clear Lake of the northern Coast Ranges. One lies between the two eastern arms of the lake in a mountain cove, the eastward opening of which has been blocked by a small lava sheet. The resulting basin, measuring a mile or more in length, is mostly occupied by a plain, but its western part is overspread after winter rains by the shallow Borax Lake, which vanishes in summer leaving a barren, white flat. A larger basin plain, measuring 1 by 4 miles, lies in an upland valley north of the lake arms; the valley outlet is reported to be blocked by a lava flow: this secluded plain presents an attractive, park-like appearance by reason of the scattered oaks that flourish on its level fields.

An extinct lake in the southern Sierra Nevada, now represented by several miles of meadows at an altitude of 8200 feet, is drained by Golden Trout Creek, which cascades down a gorge that it has cut in an obstructing lava flow in its westward descent to the canyon of the Upper Kern River. The lava flow came from a near-by cone of small size.[49]

Hot-Spring Lakes

In striking contrast to an above-described lake, the basin of which results from the solution of limestone rock in descending surface waters, are certain small lakes of Lassen Volcanic National Park. They result from the solvent action of ascending hot-spring waters which, coming from an underground source where high volcanic temperatures still prevail, rise through the lavas of extinct volcanoes, disintegrate them, carry away their more soluble minerals, and leave an insoluble residue of sticky kaolin mud on the shallow floor of the resulting cavity.

The largest and best known of these is the famous Boiling Springs Lake—Lake Tartarus of the earlier maps—which is situated at an elevation of 5750 feet in a cavity on the northeast slope of Red Mountain, near the middle of the southern border of the park. According to Day and Allen,[50] it is 220 yards across when filled to overflowing. Its shore is then marked by a chain of steaming springs and bubbling mud-pots. At times of lower water, it is more quiet. The group of hot-spring pools known as Bumpus Hell of similar origin, at an altitude of 8000 feet in a crater-shaped cavity 500 by 1400 feet across, 2 miles south of Lassen Peak, is remarkable for its boiling fountains and sulphurous

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[48] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Downieville folio (No. 37), 1897.

[49] Lawson, A. C., The Geomorphogeny of the Upper Kern Basin. Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 3, pp. 291–376, 1904. See p. 320, pls. 31, 35, 36.

[50] Day, A. T., and Allen, E. T., The Volcanic Activity and Hot Springs of Lassen Peak. Carnegie Inst. Washington Publ. 360, 1925. See pls. 8, 9; Fig. 44.

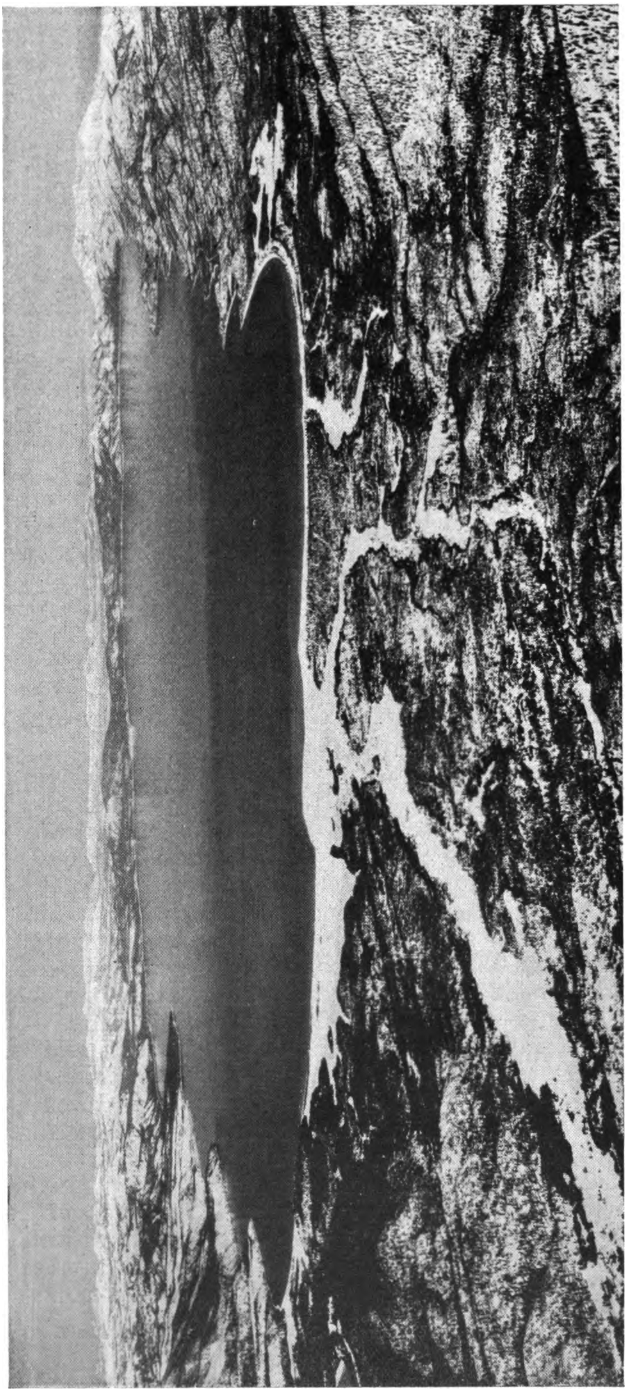

FIG. 22. Air-view of Lake Tahoe.

odors. The steam issuing from one of its roaring fumaroles had a temperature of 250° C. in 1916. The temperature of its pools was 86° C., which is the boiling point of water at that altitude.

The water of hot volcanic springs is explained by some geologists as wholly derived from the steam liberated from molten rock or 'magma', during its ascent from deep subterranean sources; it is therefore called 'juvenile' water, because it is believed never to have reached the earth's surface before. Detailed analyses of the Lassen Peak hot springs have led the above-named authors to reject this view; they regard the water of those springs as chiefly supplied, like ordinary springs, by local rainfall, and explain its high temperature by the addition of a relatively small amount of steam released from underground magmas.

Lake Tahoe and Sierra Valley

Lake Tahoe, the most famous of Californian lakes but partly included in the western angle of Nevada, deserves a section for itself (Fig. 22). It measures 21 by 12 miles, stands at an altitude of 6225 feet, and has the altogether exceptional depth of 1645 feet. Its origin is composite, as explained by Lindgren[51] and Reid.[52] It is held by a volcanic barrier in the southern part of a great, down-faulted trough, 70 or 80 miles in length, northwest-southeast, which in association with the faults of the more northern part of the Sierra Nevada described by Diller, as told above, separates some outstanding mountain blocks from the main mass of the Sierra Nevada along the northern third of its eastern border. A main scarp of the range, which here forms the western side of the Tahoe basin, may be traced more or less continuously for 120 miles northwestward. Tahoe is thus related to lakes in little filled intermont troughs, as well as to volcanic lakes.

The barrier which shuts off the basin of Tahoe from the rest of its long trough is a somewhat ancient and much dissected volcano, known as Mount Pluto, 8700 feet in summit altitude. Lindgren explains that when this great barrier was first formed, the lake rose several hundred feet higher than now. Its outlet, Truckee River, then ran northward between the western slope of the volcano and the main eastern scarp of the Sierra Nevada. The lake level was slowly lowered as the outlet cut a gorge through the lava barrier. A second rise of lake level was caused by a later lava flow which blocked the first-cut gorge, thus making the lake doubly of volcanic origin; then a second gorge was eroded and the lake was again lowered. According to Blackwelder,[53] glaciers from the west entered Truckee Canyon and built large moraines in it as much as 200 feet above the present lake level; thus obstructing the outlet for a third time and making it partly of glacial origin. Fallen Leaf and other lakes, held back by moraines on the southwestern side of Tahoe, have been mentioned above.

Lake Tahoe is probably best known outside of California from having been mentioned in "Roughing It" by the American humorist, Mark Twain, who wrote amusingly of the transparency of its waters, in which he "could see trout by the thousands winging about in the emptiness" at a depth of 80 feet. Because of its mild summer climate and of its picturesque surroundings, its shores have become a popular summer resort. A general account of the scenery of the lake in connection with its complex origin has been prepared by Louderback.[54]

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[51] Lindgren, Waldemar, The Tertiary Gravels of the Sierra Nevada of California. U. S. Geol. Survey Prof. Paper 73, 1911. See pl. 1.

[52] Reid, J. A., The Geomorphogeny of the Sierra Nevada northeast of Lake Tahoe. Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 6, pp. 89–161, 1911.

[53] Personal letter, dated July 6, 1932.

The northern part of the long, down-faulted trough was also cut off from the middle part by volcanic eruptions and there an extensive basin plain, known as Sierra Valley, measuring 19 by 15 miles at an altitude of from 4800 to 4900 feet, has been filled in with heavy detrital deposits. Like the above mentioned Indian and American valleys, not far to the northwest, this basin plain, which is today marshy in its western part, may have been at various times in its growth overspread by a shallow lake; but today it is drained nearly dry by the successful erosion of the deep gorges of Feather River through the mountains on the west.

The basins of Lake Tahoe and of Sierra Valley thus appear to be of similar origin, but they present certain contrasts. Lake Tahoe at an altitude of 6225 feet is drained to the east through a short gorge cut in its lava barrier; Sierra Valley at an altitude of about 4800 feet is drained to the west through a long canyon cut nearly all across the Sierran range. Lake Tahoe consists of a high-standing body of in-drained water, while Sierra Valley consists of a lower-standing body of in-washed detritus. The reason for the second contrast is probably to be found in part in the second lava flow on the flanks of Mount Pluto, by which Lake Tahoe was raised above the level of most of the in-filling detritus that had accumulated in the earlier formed lake; but it is probably because of the first lava flow that the much greater altitude of the Tahoe water-surface than of the Sierra Valley plain is due.

River-Made Lakes

Oxbow Lakes

Various kinds of lakes or sloughs are associated with California's larger rivers. Oxbow lakes, representing cut-off river meanders in various stages of extinction, as illustrated in Fig. 6, occur along the Sacramento with radius of quarter or half a mile, and less frequently and of smaller size along the San Joaquin. Pear Slough, near this river, is an excellent example; its name is perhaps taken from its pear-like outline. Here may be mentioned Murphy Lake, occupying a curved and narrow channel 3 miles long, northeast of the junction of Feather River with the Sacramento; also McGriff, Mary, and Horseshoe lakes, apparently of similar origin, which lie east of the Sacramento farther north.

Flood-plain Marshes

Extensive reed marshes or tulares, known as 'basins,' occur on the less aggraded lateral parts of the flood plain of the lower Sacramento River, as illustrated in Fig. 6. They may be given the appearance of large lakes when the river overflows after winter rains. Thus Sutter Basin, 10 by 2 or 3 miles, lies to the east of the river, and Yolo Basin or Slough, 20 by 4 miles, lies to the west; its less aggraded part includes a more permanent sheet of water known as Big Lake, 1½ miles in diameter. The extensive reed growth in these basins is disadvantageous in a region of moderate rainfall where the conservation of water supply becomes important, for the loss of water by evaporation from the growing reeds is many times greater than from a free water surface.[55] A similarly disadvantageous loss is suffered by the Nile where it flows through an extensive papyrus marsh many miles south of its flood plain in Egypt.

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[54] Louderback, G. D., Lake Tahoe, California-Nevada. Jour. Geography, pp 277–279, 1911.

Side-stream Lakes

The shallow valleys of small tributary streams are not infrequently laked back of the alluvial up-building of the flood plains of their trunk rivers, as in the upper right part of Fig. 6; and the backed-up lake water then invades the branches of the tributary valley just as the sea invades branching valleys on a subsiding coast and transforms them into branching bays. Such appears to be the origin of Stone Lake, with 4-mile branches, to the east of the lower Sacramento; and of Cache Slough in the extensive marshes of the Yolo Basin; and of the branched Lindsey Lake, west of the river. Also of Plumas Lake, 3 miles long backed up by Feather River flood plain; of Tracy Lake, 2 miles long with several branches, and Sycamore Slough, 3 miles long, backed up by the Mokelumne; and of Kings River Slough, held up for a slender length of 10 miles by the San Joaquin. Although these little lakes have no renown outside of the State, hardly indeed, outside of their county, they provide for their neighboring residents a pleasing departure from the monotonous flatness which characterizes scores and scores of miles of the vast intermont plain, known as the Great Valley.

An example of a laked side stream in a mountain valley is found in the curved range which encloses the Great-Valley plain on the south. The upper part of Grapevine Canyon, the mouth of which holds an extinct landslide lake as told above, has a flat floor heavily aggraded with detritus, perhaps supplied by a landslide in its headwaters. In consequence of this a side valley up stream from Old Fort Tejon is ponded in the shallow Lake Castaic; but the lake is often dried off and then one sees only its white, playa-like bed. This lake "is of gruesome memory; for old-timers will tell you that once upon a time some exasperated white men, of the type that modern lynchers are made of, drove a whole village of Indians, men, women, and children, into it, because it was assumed that some of the number were responsible for the murder of the cook and a boy at Fort Tejon." [56]

Many little wet-weather ponds, from a quarter of a mile to a mile across, are found on the plain of the Great Valley between San Joaquin and Kings rivers, as shown on Conejo, Fresno, San Luis Ranch and Ingomar sheets of the U. S. Topographic Map. Their origin is not clearly understood.

Lakes barred by Fan Deltas

A few small examples of lake of this class have already been given; first, the little Blue Lakes that are associated with the above-described

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[55] State of California, Dept. of Public Works, Water Resources Bull. 28, 1931. See p. 253.

[56] Saunders, C. J. The Southern Sierras of California. Boston, 1923. See p. 74.

Clear Lake of landslide origin; later, the glacial Twin Lakes that are divided by the fan-deltas of opposite side streams. The examples now to be described are of much greater size. The extensive and low-grade detrital fans that are spread out by Kings and Kern rivers as their contribution to the vast intermont basin-plain of the Great Valley, have obstructed the weak drainage of its drier southern part, and evanescent lakes have thus been formed. Tulare (Spanish for reed-marsh) Lake, south of Kings River fan, was formerly a shallow water-sheet, many miles across; it is now hardly more than a marsh, since the greater part of its water supply has been withdrawn for irrigation.

The following account of the extinct Tulare Lake is condensed from the "Official Historical Atlas of Tulare County," published in 1892 by the County Supervisors. In the early years of American occupation the lake measured at high water 44 by 22 miles and its area was 760 square miles; in 1891, it had shrunk to 22 by 17 miles and its area was 195 miles. It fluctuated greatly in level, having stood at 220 feet above Suisun Bay in 1862 and 192 feet in 1883. In the flood season of 1862 the attempt was made to run a stern-wheel steamboat from the San Joaquin River to the lake, but the steamer grounded and for many years after the hull and the stern-wheel were incongruous objects on the dry plain. However, in 1875 a small steamboat was built on the lake and used as a pleasure and freight boat for some years; several smaller boats have also been launched there for business and pleasure. In 1891 fish abounded, and terrapin were shipped in large quantities to the San Francisco market. The shallow waters as well as the surrounding marshland were then a favorite resort for water fowl, such as swans, cranes, curlews, duck, geese, and snipe.

Buena Vista and Kern lakes, 7 by 5 and 6 by 4 miles when flooded, are shallow and vacillating water sheets near the southern end of the Great Valley plain, where they are held by the low delta of Kern River just as Tulare Lake was formerly held by the delta of Kings River. They are said to be reduced to hayfields in summer, and even in winter their flooding is lessened by a canal leading northward where the front of the delta meets the western hills. The plain of Buena Vista Lake, shown on Mouth of Kern topographic map, does not vary 5 feet in altitude across a breadth of 6 miles.

By far the largest delta-barred basin in California, and probably the largest in the world, is found where the northwest end of a great intermont trough of depression is separated by the delta-plain of the Colorado River from its much longer and deeper southeastern part, which is occupied by the Gulf of California. As first described many years ago by Blake,[57] the basin was thought to have been occupied in large part by the head of the Gulf before the delta barrier was built; but it was understood that "occupation of the valley by sea water * * * has extreme antiquity * * * dating back to Middle Tertiary," and that it gradually became fresh because of the flow of the Colorado River into it and its outflow by a channel along the delta front. The modern disappearance of the resulting lake was ascribed to evaporation in the arid climate there prevailing.[58] Later studies, especially those of Free[59] and Buwalda,[60] recognize the effectiveness of the delta barrier, but explain the basin that it encloses by the progressive depression of the land during the time of delta growth, so that although 2200 square miles of the basin floor are now below sea level, the deepest part being 275 feet below, it has never been overflowed by sea water.

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[57] Blake, W. P., Ancient Lake in the Colorado Desert. Am. Jour. Sci., 2d ser., vol. 17, pp. 435–438, 1854.

[58] Blake, W. P., The Cahuila Basin and the Desert of the Colorado. Carnegie Inst. Washington, Publ., 193, pp. 1–12, 1914. See p. 3.

The recent depression of the floor is attested by the occurrence of low fault scarps which cross the piedmont detrital fans built on the basin margin by inflowing wet-weather streams. The salt beds of the basin floor have been shown by Ross[61] to be of such composition that they are best explained, not by evaporation of an enclosed arm of the sea, but of a river-fed fresh-water lake. That such a lake has existed there is shown by its shore lines, about 30 feet above sea level; it must have been formed when the Colorado happened to flow westward into the basin, and the southward outlet of the lake must have followed the margin of the delta where it abuts against the western mountains. The lake necessarily disappeared by evaporation when the river chanced to give up its westward course and flow southward directly to the Gulf.

The present Salton Sea is a temporary water body that was formed on the floor of this great delta-barred basin by the accidental overflow of the Colorado River between 1905 and 1907. The water body then gained a size of 17 by 43 miles and an area of 410 square miles with a maximum depth of 83 feet, and thus became the largest lake in the State. Its area is now slowly decreasing by evaporation and it is destined to disappear. Accounts of it have been prepared by several observers.[62]

Plunge-Pool Lakes

A pool is excavated by the plunging water of a cataract. The plunge-pool of this kind beneath Niagara is about as deep as the falls are high. If the Niagara River were diverted to another course the pool would hold a small lake at the head of the river gorge. Some small lakes of this kind are known in south-central Washington, where the Columbia River, turned in the Glacial Period from its great northwest bend by the large Okanogan glacier from British Columbia, ran by a more direct course across the lava plains toward its canyon through the Cascade Mountains. It cut back a gorge on that temporary course, at the retreating head of which it plunged down in a great cataract, subdivided by several projecting ledges in the gorge-head cliff. When the invading Canadian glacier disappeared on the return of a milder climate in the Postglacial or present epoch, the river resumed its roundabout course and left the temporary course dry, except that several little lakes occupy the pools excavated by the plunging cataract. The site of the vanished cataract is now deservedly protected as a National Monument.

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[59] Free, E. E., Sketch of the Geology and Soils of the Cahuila Basin. Carnegie Inst. Washington, Publ., 193, pp. 21–33, 1914.

[60] Buwalda, J. P., The Salton Basin, Southern California. Science, vol. 71, pp. 104–106, 1930.

[61] Ross, W. H., Carnegie Inst. Washington, Publ., 193, pp. 35–46, 1914. See p. 46.

[62] Mendenhall, W. C., Ground Water of the Indio Region. . . . . U. S. Geol. Survey Water-Supply Paper 225, pp. 21–24, 1909.

MacDougal, D. T., and others, The Salton Sea. . . . . Carnegie Inst. Washington, Publ., 193, 1914; also Am. Jour. Sci., 4th ser., vol. 39, pp. 231–250, 1915.

Kennan, George, The Salton Sea, 1917.

Mention is made of this kind of lake in order to note that miniature water pools of the same kind occasionally occur in the valleys of desert mountain ranges in the southeastern part of the State, where short-lived torrents fed by summer cloudbursts excavate minute plunge-pools along their steep courses. The pools are known as 'tanks,' and also by the Spanish name, 'tinajas,' or water jars. They are usually more or less filled with boulders and gravel, but they also hold water for a time after a flood and are then the only available water supply

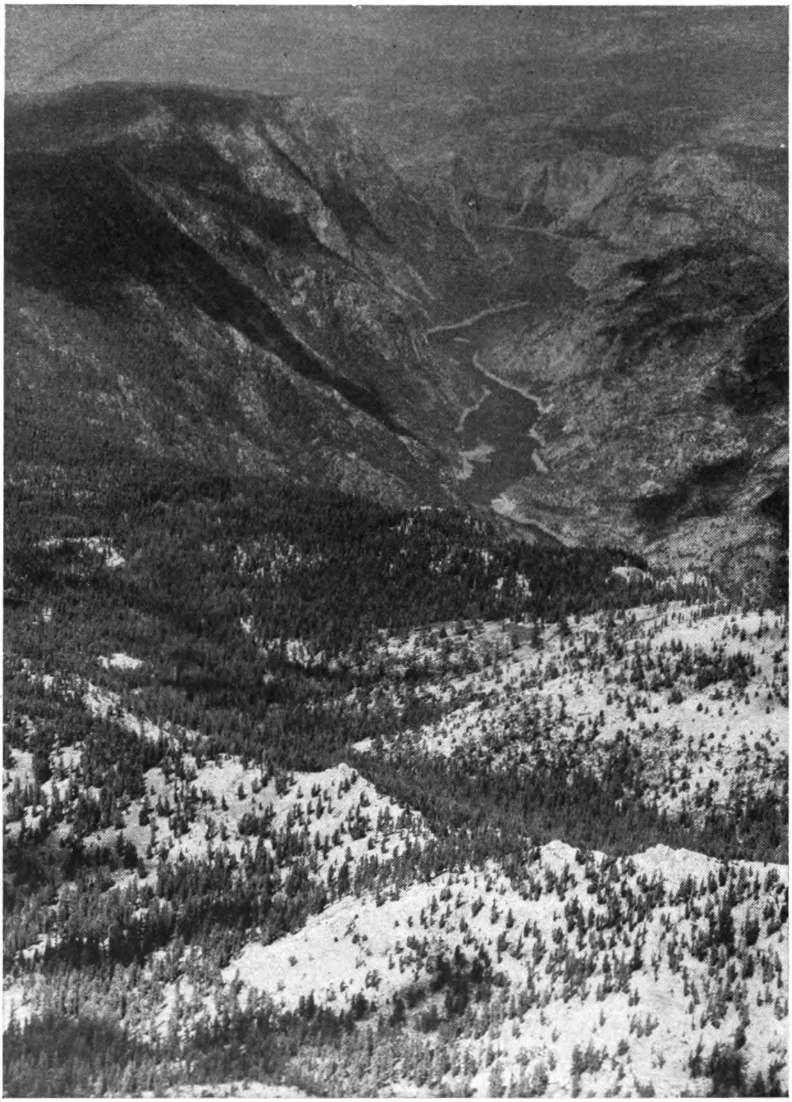

FIG. 23. Air-view of Hetch Hetchy Reservoir.

for miles around. Where water is priceless, little tinajas may rank as lakes.

The McCoy tanks are in a range of the same name 20 miles west of the lower Colorado. One of them is "a little bowl in porphyry. It is water-tight and holds water for several months." Farther north in the Little Maria Mountains, Mohave tank in granite has been "formed by flood waters pouring over a cliff about 15 feet high in the canyon bed"; in October, 1917, "a pool of water 12 to 15 feet in diameter and 2 to 3 feet deep stood in the little basin." It has never been known to be entirely dry and is "a favorite watering place for mountain sheep and other wild animals."[63] A detailed account of some remarkable tinajas in Arizona is given by Bryan.[64]

Lake-Like Reservoirs

Artificial reservoirs, constructed for the irrigation of agricultural lands or for the supply of municipal districts or of electric power stations, are truly lake-like in their appearance. Such reservoirs should be deep enough to prevent the growth of reeds, because when reeds are present they cause a great increase of evaporation, as noted above in the account of flood-plain marshes. A number of reservoirs are, indeed, natural lakes artificially enlarged. Some of these water bodies, like the backed-up lakes mentioned in the second preceding section, illustrate very clearly the manner in which the valleys of a subsiding coast are converted into bays. Many small reservoirs are not here listed.

Clear Lake, second largest of its name and already described as occupying a fault basin in the northeastern part of the State, is now enlarged in a reservoir measuring 8 by 3 miles. Big Sage, Thomas and Tule Lake reservoirs, of smaller size, the latter not to be confused with the vanishing Tule Lake farther north, are held in branch valleys of Pit River south of Goose Lake, and Britton reservoir is held in the valley of Pit River itself where it is cut through the northern mountains between Mt. Shasta and Lassen Peak. Mountain Meadow and Almanor reservoirs, 6 by 2 and 13 by 5 miles, lie in valleys of the North Fork of Feather River at the northern end of the Sierra Nevada proper, 25 and 35 miles west of Honey Lake: the former submerges part of Big Meadows, above described as the bed of a lava-barred lake; the latter is the largest reservoir in the State.

Farther south and mostly in or near the foothills of the Sierra Nevada, Pardee reservoir, 8 miles long, is on the Mokelumne; Woodward, 3 miles long, is on a small stream east of Stockton, and Melones, 5 miles long, is on the Stanislaus River. The glacial Lake Eleanor, 1 by 1½ miles, in the mountains on an upper branch of Tuolumne River, has been enlarged in a reservoir 2½ miles in length.

On the upper Tuolumne is the famous Hetch Hetchy reservoir (Fig. 23), 8 miles long, in a wonderful trough of the Yosemite type. The proposed construction of this reservoir aroused nation-wide opposition. Many lovers of nature, among whom John Muir was most widely known, protested that the great scenic attractions of the valley would

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[63] Brown, J. S., The Salton Sea Region, California. U. S. Geol. Survey Water-Supply Paper 497, 1932. See pp. 111, 264, 275, 276.

[64] Byran, Kirk, The Papago Country, Arizona. U. S. Geol. Survey Water-Supply Paper 499, 1925. See pp. 123–131.

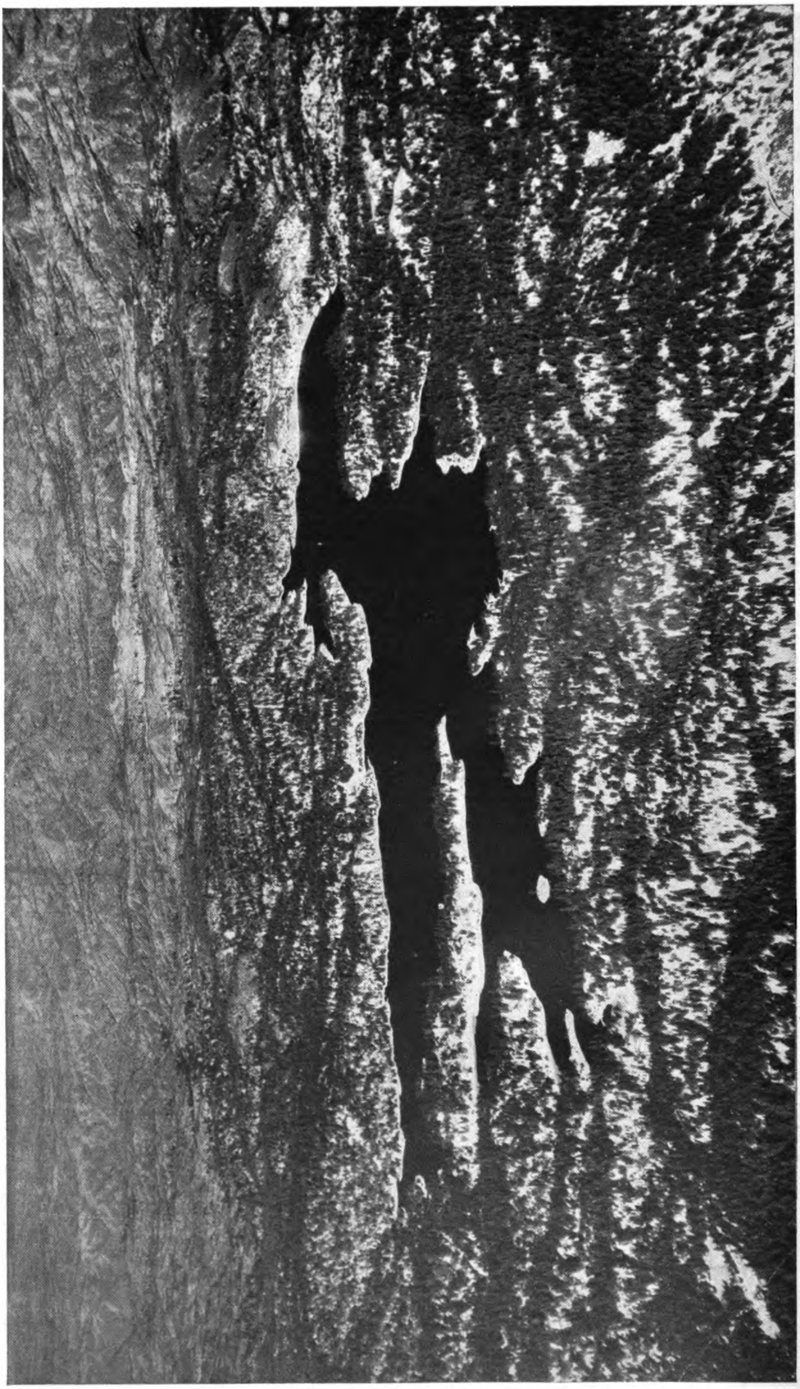

FIG. 24. Air-view of Arrowhead Reservoir.

be diminished if it were laked;[65] but the pressing need of a better water supply for the cities of the San Francisco peninsula, supported by the profitable use of the water in its descent from the high-level reservoir in furnishing electric power, overcame the esthetic protests. Although a reservoir in a mountain valley is evidently a modification of nature, it is not necessarily a disfigurement; and the artificial production of a beautiful reservoir in Hetch Hetchy Valley may be taken as a compensation for the destruction by natural processes of the lake which in prehistoric times beautified the Yosemite.

Farther down Tuolumne River are Don Pedro reservoir, measuring 7 miles in its bent length, and Owens reservoir, 4 miles long. Exchequer reservoir on the lower Merced River is of irregular outline and measures 12 miles in its winding length. In Owens Valley at the eastern base of the southern part of the same range, Upper and Lower Haiwee reservoirs, each about 3 miles long, are on the line of the Los Angeles aqueduct, south of Owens Lake.

Bear Lake, 6 miles long, and Arrowhead Lake, 2 miles long, are reservoirs in the highlands of the San Bernardino mountains; the latter is shown in Fig. 24.

All these reservoirs resemble Clear Lake of the northern Coast Ranges, in that their dams obstruct valleys very much as its landslide does; but few reservoirs resemble Clear Lake in having their outflow diverted from the valley by which their waters were formerly discharged. Two exceptional cases somewhat of that kind deserve special mention: One is Echo Lake, south of Lake Tahoe, already mentioned as having its waters diverted from the north and east-flowing Truckee River to the headwaters of the west-flowing South Fork of American River. The other. Pilsbury reservoir, 6 by 2 miles, occupies the branching headwater valleys of Eel River in the Coast Ranges, about 20 miles north of Clear Lake: its outflow runs down the valley to the much smaller Van Arsdale reservoir, but there the outflow is led by a tunnel through a ridge at the head of Potter Valley, where it joins the East Fork of Russian River. In the same region of the Coast Ranges are East Park and Stony Gorge reservoirs, 25 and 35 miles northeast of Clear Lake.

In the San Francisco peninsula south of the Golden Gate the long trough that has been eroded on the San Andreas rift holds two reservoirs, known as San Andreas and Crystal Spring lakes, 3 and 6 miles long when filled to capacity. In the Mt. Hamilton Range southeast of San Francisco Bay, two reservoirs, Chabot, 2 miles long, and Calaveras, 3 miles long, contribute to the pressing need of larger water supply for the growing bay cities.

Santa Barbara reservoir, 4 miles long, is in the valley of the Santa Inez River, north of the east-west mountain range of the same name. Arrowhead reservoir, 2 miles long, and also the artificial enlargement of the above-mentioned Bear Lake, 5 miles long when filled to capacity, are on the highlands of the San Bernardino and San Gorgonio mountains. Inland from San Diego and not far north of the Mexican boundary are Sweetwater, Lower Otay, Barrett and Moreno reservoirs, 4, 3, 6, and 3 miles in length. Farther north are the slender Hodge reservoir, 6 miles long, and the broader Henshaw reservoir, 5 by 4 miles.

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[65] See Muir's article, The Hetch Hetchy Valley, Sierra Club Bulletin, vol. 6, pp. 211–222, 1908, which includes a fine view of the valley in its natural state.

Here may be briefly mentioned the shallow water sheets of artificial origin, covering square-mile sections or quarter-sections on the level, Great Valley plain, maintained by various gun-clubs in order to attract migrating water-fowl. Several of them are shown on the Hamlin School and Miramonte sheets of the U. S. Topographic Map. They remain dry through most of the year, but are flooded by pumping up ground water late in the autumn and so remain into the winter. It is estimated that 1,000,000 wild ducks are shot yearly on these ponds. In their temporary existence they are but little longer lived than the mirages of the desert playas.

The Nile has a lake-like appearance where it spreads over its flood plain above the great dam at Assouan in Egypt. A great and deep-branching lake is now in process of production on the Colorado River by the building of the Hoover Dam in Black Canyon, to which the name of Boulder Canyon, next upstream, is popularly given.

Lake-Like Bays and Lagoons

A number of coastal bays, more or less completely enclosed from the ocean, gain a lake-like appearance. One of them, the Bay of San Francisco, by far the greatest in area as well as in importance in California, is also one of the most famous arms of the sea in the world. Like other famous sea arms, such as the magnificent bay on which the city of Rio de Janeiro is situated in Brazil, or the beautiful bay on which Sydney is situated in Australia, this lake-like bay in California is due to the submergence of former valley-like lowland areas in consequence of a slight subsidence of its district, and the same subsidence converted a former river-cut gorge in the coastal mountains into the famous Golden Gate.

Although the original area of the bay has been considerably diminished by the growth of salt marshes in its shallow shore waters, the main body, San Francisco Bay, still measures 47 by 5 to 12 miles; its northern extension, San Pablo Bay, set apart from the main body by a peninsular arm of the east shore, is 14 miles across; here the muddy water from the rivers of the Great Valley and the clearer water of flood-tide from the ocean are often distinguishable on opposite sides of the bay by their contrasted colors. The innermost reach above Carquinez Narrows is Suisun Bay, 14 by 2 to 6 miles, much shoaled and encroached upon by the marshy delta-lands of the Great Valley rivers.

This great bay may be compared with Clear Lake, in the Coast Ranges 100 miles to the north, because, as has been told on an earlier page, the lake, like the bay, has recently flooded part of an aggraded intermont plain. To be sure, the bay is of salt water at sea level, while the lake is of fresh water at an altitude of 1300 feet; the bay has flooded a large part of an extensive pre-existent plain because that part of the plain was depressed below sea level, while the lake has flooded part of a smaller plain because the drainage outlet of the plain was recently obstructed by a landslide; the bay has become an active center of population, industry and commerce, thereby gaining world-wide fame, while the lake preserves a quiet, rural quality which adds to its charm; but the resemblances of the two as well as their differences deserve recognition.

All the other lake-like bays of the California coast are of much smaller size. Beginning at the north they are as follows: Earl Lake, 1 mile by 6, and Talawa Lake, about 3 miles long, are both, the first behind the second, enclosed by a long, wave-built, smoothly beached sand reef, which swings out to a low rocky headland next north of Crescent City, 10 miles south of the Oregon line. The two lakes are separated by a narrow strip of sand which may be an earlier-formed reef of somewhat sharper curvature than the outer reef; for such curvature would have suited the beach drift very well before the cliffs to the north were cut back as straight as they are now. On smoothly curved beaches of this sort (Fig. 25), in adjustment with the approach of the surf because formed under its control, a long line of breakers plunges almost simultaneously in calm weather for miles together.

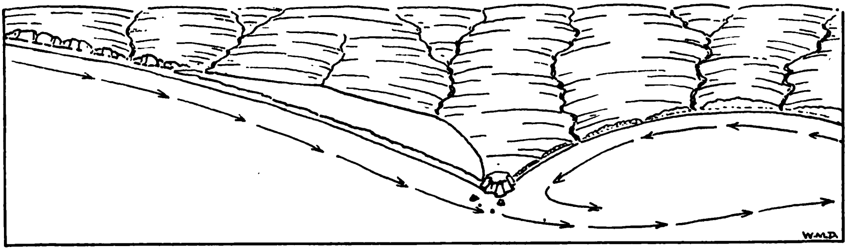

FIG. 25. Diagram of lagoon enclosed by a wave-built beach.

In consequence of a slight submergence of the coast, Klamath River is embayed for about 2 miles back from its mouth, which is partly closed by a sand spit. Farther south, where the strongly cliffed coast is adventurously followed by the Redwood Highway high above sea level, three valleys, slightly embayed by the same submergence of the coast, are closed somewhat as in Fig. 26 by heavy sand reefs, on which drift logs abound: the first is Freshwater Lagoon, Fig. 27, about a mile across its front; closely following is Stone Lagoon of larger size; third and farther south is Big Lagoon, 3 miles across. The

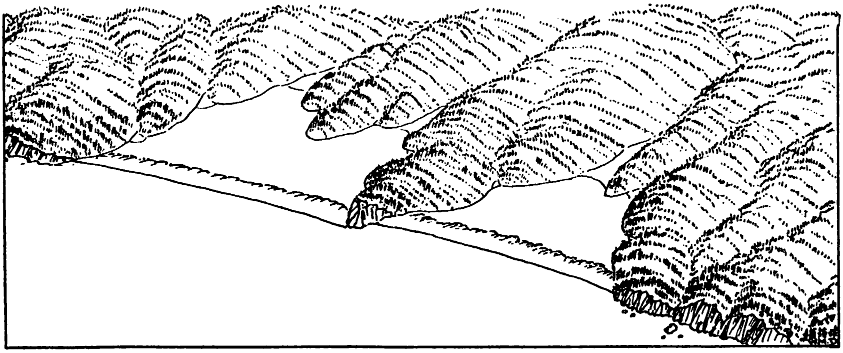

FIG. 26. Diagram of lagoons enclosed by wave-and-current-built beach on a coast embayed by slight subsidence.

fresh water in these enclosed bays, supplied by streams and springs from the backland, stands a little higher than mean sea level and is discharged by percolating through the enclosing sand reef. Roughly 20 miles farther south the saline waters of Humboldt Bay appear to invade three separate valleys, all enclosed by a single sand reef with a tidal inlet near the middle of its 13 miles of length; the northern and southern embayments are each 4 miles long; the middle one has a much smaller inland reach; all are diminished in area by invading deltas. The city of Eureka lies next south of the northern embayment. Eel River, 5 miles to the south, might also mouth in a bay, had it not been silted up by that good-sized stream, which is many times larger than the little creeks of the Humboldt embayments.

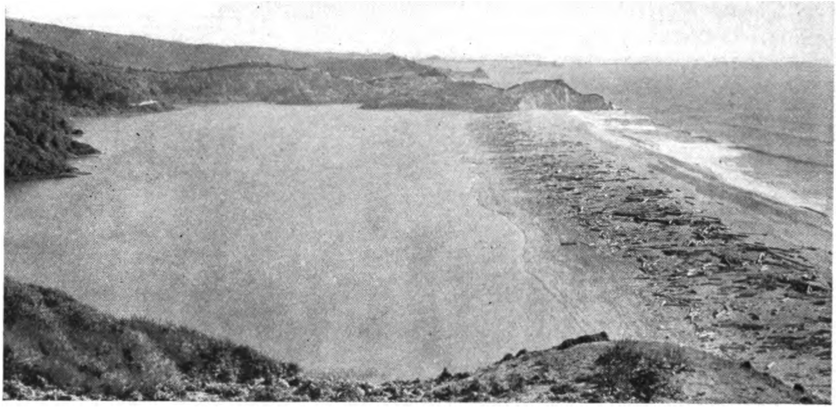

Photo by Patterson Bros., Santa Rosa.

FIG. 27. Freshwater Lagoon, below the Redwood Highway, north of Eureka; looking south.

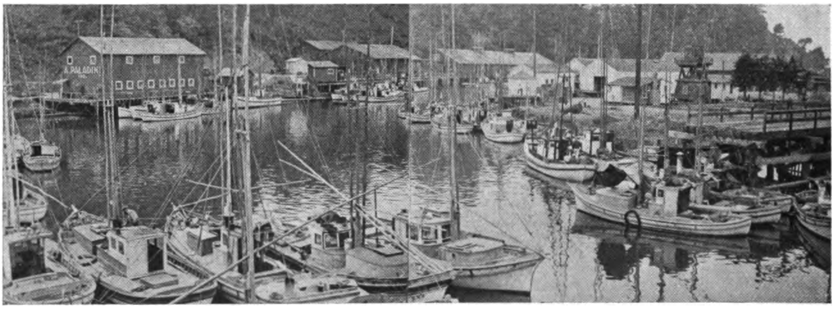

Photo by Olaf P. Jenkins.

FIG. 28. The embayed mouth of Noyo Creek, Mendocino County.

No bays of importance are found in the following 170 miles of the mountainous and boldly cliffed coast; but practically all the streams, none of them of great size, which there issue from the mountains, mouth in small fresh-water lagoons held back by heavy beaches. The streams may break through the beaches at times of flood; at other times their small discharge is accomplished by percolation through the beach sands. One such enlarged stream, the Noyo, Fig 28, offers a striking contrast to its solitary neighbors as it swarms most picturesquely with little fishing boats, for which an artificial cut through the enclosing beach is maintained; not that the slightly enlarged stream is a commodious harbor, but that the cliffed outer coast is absolutely harborless. Several other similarly enlarged streams served as local harbors for the lumber industry some 15 or 20 years ago; but their use has now either decreased or ceased with the decline of lumbering thereabouts.

At the end of the 170-mile stretch of harborless coast Russian River, having made its way in a fine, 13-mile gorge through the coastwise ranges, is enlarged by slight submergence into an estuary a mile or more in length, nearly closed at its mouth by a beach, of which Holway gives a good illustration.[66] Five miles farther on, Bodega Head, originally a two-mile, rocky island separated by a mile-wide strait from the coast, is now land-tied by a broad beach which is swept out to it from the shore on the north by the long-shore beach drift, thus transforming the strait into a bay open to the south; and a smaller beach, built by a backset or beach drift from the shore on the south, nearly encloses the bay; only a narrow tidal inlet is left open next to the end of the rocky island. A striking feature of the bay is the great drove of large dunes, the sands of which, impelled by north-west winds, are slowly climbing over the broader beach and the northern part of the rocky island and invading the bay, somewhat as drawn in Fig. 29. The dunes make a delightful summer picnic ground when the inland plain of the Great Valley is blazing hot!

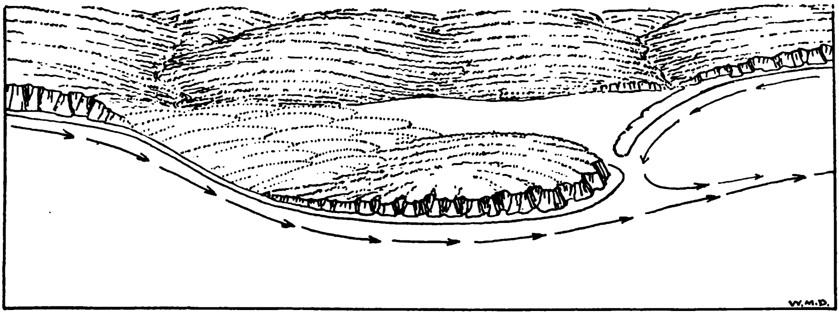

FIG. 29. Diagram of a land-tied island with a bay behind it, closed by a sand-reef beach controlled by a back-set eddy current.

Two miles to the south is the little Estero Americano, or American Estuary, like the Russian River estuary except in being of much smaller size and more completely closed. Then come Tomales and Bolinas bays, which head against each other in the party submerged depression that has been worn down on the shattered rock of the San Andreas rift, and which thus nearly insulate the Point Reyes peninsula. The strait that has been transformed into the above-named Bodega Bay lies in the northern continuation of this rift depression. Tomales Bay, opening to the north, is 16 miles long by a mile or so wide; it is imperfectly enclosed by a beach and bar, wave-driven from the north. Bolinas Bay, originally opening to the south and measuring 1 by 4 miles, is now almost closed by Stinson Beach, which is driven obliquely across its mouth by a backset beach drift from the south. The sands for this beach appear to be derived chiefly from the cliffs south of the Golden Gate, whence they travel 20 miles northward, making their way across the entrance to the Golden Gate along its offshore, submarine bar, curved on a 5-mile radius, before reaching the beach.

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[66] Holway, R. S., The Russian River, a Characteristic Stream of the Californian Coast Ranges. Univ. Calif. Publ. Geogr., vol. 1, pp. 1–60, 1913.

It is because of this northward shift of the sands that the surviving inlet of Bolinas Bay is at the northwest end of the enclosing beach; and it is because Bolinas is much smaller than Tomales and therefore has weak tidal currents that it is so much better enclosed. Its inlet exhibits a typical example of what may be called a double-headed tidal delta, the outer head of which is built out in a slight salient by the ebb tide and smoothed off by the shore waves, while the much larger and more freely branching inner head of the delta is built by the flood tide in the quiet waters of the bay.

On the south side of Point Reyes peninsula, which makes out between Tomales and Bolinas bays, is Drakes Estero, a fine embayment 4 miles long, with 3 arms that branch into as many valleys in the hilly uplands; it is enclosed by a beach formed by back-set drift, farther northwest than the one which encloses Bolinas Bay. Three smaller embayments of similar origin are near by; two lie next to the east on the southern coast, and one on the northern coast of the wave-trimmed peninsula.

Five miles south of the Golden Gate is Merced Lake, a true lake in being of fresh water, with two 2-mile arms that enter the hills of the San Francisco peninsula and are enclosed by the broad beach of its ocean shore and by the sand dunes that are swept by the westerly winds from the beach.

Several lagoons lie back of the 25-mile beach and dunes of the wide-open Monterey Bay, the middle of which lies 80 miles south of the Golden Gate. Two of the largest are expansions of Salinas and Pajaro rivers; but three others, one of which is known as Elkhorn Slough, do not appear to be related to stream courses. Some of these lagoons communicate with the ocean by narrow tidal inlets, but the Salinas lagoon is enclosed by a sand beach, except when floods from winter rains break through it. Near the southern end of the long beach several minute brackish or salt pools, which are said by Galliher in his account of Monterey Bay to have biological affinities with desert saline lakes,[67] lie back of the invading dunes.

Farther south, the bold and strongly cliffed coast of the Santa Lucia Range extends practically without a bay for 100 miles. All of the streams that here discharge directly to the ocean are of small size; they seem to be slightly embayed by submergence and the little coves are lagooned by beaches. Beyond this long and high range, which runs parallel to the coast, are several shorter ones which trend more to the southeast and head abruptly at the shore. Between them lie aggraded plains, well beached and duned; and back of the first beach of this series is Morro Bay, 3 by 2 miles, the beach of which has been guided by back-set beach drift. The town of San Luis Obispo stands at the head of the plain, 13 miles back from the bay. The next intermont plain, on which Santa Maria is the chief town, is heavily invaded by dunes from its beached front: here, a few miles inland is the small Guadalupe Lake; it was probably of greater size before the invasion of its area by dunes.

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[67] Galliher, E. W., Sediments of Monterey Bay, California. California State Min. Bur., Mining in California, January, 1932, pp. 42–79, 1932. See Fig. 5 and pl. III.

Then for over 30 miles southward to Point Conception, for 60 miles eastward along the Santa Barbara coast of the east-west Santa Inez Range, and for 30 miles southeastward along the lower Ventura coast to the east-west Santa Monica Range, no bays or lagoons are mapped, apart from a few small pools, such as those back of the long Hueneme beach of the Oxnard plain in the last 10 of the total 120 miles. Only at the end of that distance is there a narrow, beach-enclosed, tidal lagoon a few miles in length at the western end of the Santa Monica Range.

The 30-mile southern coast of that range is again without embayments; and not till a long beach swings southward from it is a little tide-marsh bay enclosed in the low coast lands; the shore resort of Venice lies on the enclosing beach, 15 miles west of Los Angeles. A few miles farther south rises the promontory of the San Pedro Hills, formerly an island; after it is rounded and the coast trends east again, Wilmington Lagoon, 3 miles long with 3 miles more of tidal marsh, lies back of a long beach that has been built westward by back-set beach drift, so that its tidal inlet is driven against the eastern base of the San Pedro Hills.

The back-set beach drift which has built this beach is, like several other drifts of the same kind mentioned above and one more to be mentioned below, the result of a coastal promontory or salient which holds the dominant southeastward sea current offshore. The lagoon, now provided with an artificial entrance cut through its beach and improved with wharves and docks, serves as the harbor for the growing maritime commerce of Los Angeles, which lies 20 miles inland to the north. The shore resort of Long Beach is at the east end of the lagoon. Beyond it are four more beach-barred lagoons of smaller size.

Farther on still is a marsh that might be a good-sized beach-barred bay, had it not been silted up by the Santa Ana River, the largest stream of southern California. Then comes the bay known as Newport Harbor, 5 miles long at high time, shut in by a broad, wave-driven and southward-growing beach, on which a summer population gathers; the tidal currents at the harbor entrance are dangerously strong; the Santa Ana River, deflected southward by the wave-driven beach, used to mouth through this bay; it now has an artificial mouth farther north, cut through the long beach that encloses its marshes.

The following coast is, apart from two small salients, rather smoothly cliffed and beached in a long southeastward curve for over 60 miles; but near the middle of that distance half a dozen small streams, apparently a little drowned at their mouths and more or less marshed, are beach-barred. Next comes Soledad Mountain back of La Jolla, beyond which False Bay is another beach-enclosed embayment, 2 by 3 miles, again with dangerous tidal currents at its inlet. Finally, beyond the southward-stretching peninsula of Point Loma, San Diego

Bay is reached, 12 by 2 or 3 miles, enclosed by a long beach, built northward from near the Mexican boundary by a wave drift to the low Coronado Island. This beach, 12 miles in length, is the finest example of its bay-enclosing kind in the State. One of the longest beach-enclosed lagoons in the world stretches northward for scores of miles in a graceful curve from the Rio Grande delta along the low coast of Texas.

Conclusion

In closing this review the author desires to remind his readers once more that the study of Californian lakes is by no means complete. It is therefore eminently possible that further investigations will lead to many new descriptions as well as to corrections in some of the foregoing descriptions. But if lovers of nature, young as well as older, gain an increased enjoyment of Californian lacustrine scenery by reason of what is here told of its origins, and if some of the more observant among them are thereby incited to make new investigations of the ways in which Californian lakes are brought into being, the enjoyable labor of gathering the material presented above will be doubly repaid.

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